AD-A033 187 TITANIUM METALS CORP OF AMERICA TORONTO OHIO TIMET DIV F/G 11/6
FORMABLE SHEET TITANIUM ALLOYS.(U)
AUG 76 G LENNING F33615-74-C-5063
UNCLASSIFIED AFML-TR-76-45 NL

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AFML-TR-76-45

FORMABLE SHEET TITANIUM ALLOYS

TIMET DIVISION
TITANIUM METALS CORPORATION OF AMERICA
TORONTO, OHIO

AUGUST 1976

TECHNICAL REPORT AFML-TR-76-45
FINAL REPORT FOR PERIOD MARCH 1974 - DECEMBER 1975

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AIR FORCE MATERIALS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
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19 REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
18 1. REPORT NUMBER AFML-TR-76-45	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) 6 Formable Sheet Titanium Alloys		9 5. TYPE OF REPORT & PERIOD COVERED Final Technical Report, 1 March 1974 — Dec 1975
		6. PERFORMING ORG. REPORT NUMBER 15
7. AUTHOR(s) 10 G. Lenning		15 8. CONTRACT OR GRANT NUMBER(s) USAF F33615-74-C-5063
9. PERFORMING ORGANIZATION NAME AND ADDRESS TIMET Division Titanium Metals Corp. of America Toronto, Ohio		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Materials Laboratory Air Force Systems Command United States Air Force Wright-Patterson AFB, Ohio		11 12. REPORT DATE August 1976
		13. NUMBER OF PAGES 179
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) 12 193p.		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

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17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

16 7351 17 05

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Mill Processing	Ti-15V-3Cr-3Al-3Sn
Formability	Ti-8V-7Cr-3Al-4Sn-1Zr
Formageability	Ti-8V-4Cr-2Mo-2Fe-3Al
Simulated Strip Rolling	
Hydroforming	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The objectives of this program were to evaluate three promising experimental alloys by optimizing mill processing using formability, formageability, and uniformity and consistency of properties as the criteria. The three alloys 1) Ti-8V-7Cr-3Al-4Sn-1Zr, 2) Ti-8V-4Cr-2Mo-2Fe-3Al, and 3) Ti-15V-3Cr-3Al-3Sn were selected under Contract No. F33615-72-C-1696, "Development of Economical Sheet Titanium Alloy". over

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20. ABSTRACT - continued

Both of these programs represent a continuation of studies begun at Battelle under Contract No. F33615-69-C-1890 and continued at Lockheed under Contract No. F33615-71-C-1682.

The three mill processes examined were:

1) Conventional cold strip processing

2) Conventional hot mill processing to plate followed by cold hand mill rolling to sheet

3) Conventional hot mill processing

The materials from the two cold roll processes showed the better forming potential and were selected for extensive mechanical property and formability evaluation. The formability study included successful cold hydroforming of aircraft parts at Rockwell International's, Columbus, Ohio Division. All three alloys offer improved mechanical properties over those for existing titanium sheet alloy airframe materials. Further work is recommended for one or more of these alloys because of the combination of economy in formed parts and mechanical properties.

FOREWORD

This report was prepared by the Toronto Technical Laboratory, TIMET Division of Titanium Metals Corporation of America, Toronto, Ohio, under USAF Contract No. F33615-74-C-5063. The research was performed under Project No. 7351 "Metallic Materials," Task No. 735105 "High Strength Metallic Materials." The work was administered by the Metals and Processing Branch, Metals and Ceramics Division, Air Force Materials Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, with Mr. W. R. Kerr, AFML/LLS as Project Engineer.

This report covers the period from 1 March 1974 to 15 December 1975. The project manager was G. Lenning. Ingot melting was under the direction of Messrs. H. R. Palmer and R. E. Adams. Analytical determinations were directed by Ms. D. R. Valent. Material fabrication was directed and monitored by the project manager. Pole figures and x-ray phase identification were supervised by Dr. H. W. Rosenberg. Tuckerman Modulus and crack growth testing was supervised by Dr. Rosenberg and Mr. T. L. Wardlaw. The "Room Temperature Formability Evaluation" was conducted at the Columbus Aircraft Division of Rockwell International under a sub-contract from TIMET. At Rockwell the study was supervised by Messrs. D. L. Day and A. Shames.

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SECTION I

INTRODUCTION

This program was aimed at exploring and selecting optimum mill processing procedures for three promising experimental alloys on the basis of formability, formageability, and uniformity and consistency of properties. The alloys selected were Ti-8V-7Cr-3Al-4Sn-1Zr, Ti-8V-4Cr-2Mo-2Fe-3Al, and Ti-15V-3Cr-3Al-3Sn. These alloys were selected from a prior program as having potential for good fabricability and aging response to high strength and toughness. Melting and projected mill process economics were also criteria for the previous program conducted on Contract No. F33615-72-C-1696[(1)]. This prior contract represented a continuation of a program begun at Battelle under Contract No. F33615-69-C-1890[(2)] and continued at Lockheed under Contract No. F33615-71-C-1682[(3)]. One of the three alloys selected, Ti-15V-3Cr-3Al-3Sn, was from the Lockheed program. Beyond the alloy criteria noted above, athermal matrensite compositions were avoided.

Near the conclusion of the program on Contract No. F33615-72-C-1696 an Air Force-Industry Workshop on Formable Titanium Sheet was conducted[(4)]. Two of the general conclusions derived from this workshop gave strong support to the expectations for the cold rolled strip process to be developed on this program:

1) Improved product uniformity with respect to dimensional tolerance, surface finish, and properties over those of existing hand mill products would provide cost savings in fabrication of parts.

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(1) Wardlaw, T.L., Rosenberg, H.W., Parris, W.M., Titanium Metals Corp. of America, Technical Report AFML-TR-73-296, Contract No. F33615-72-C-1696, January 1974.

(2) Wood, R.A., Williams, D.N., Boyd, J.D., Rothman, R.L., and Bartlett, E.S., Battelle Memorial Institute, Technical Report AFML-TR-70-257, Contract F33615-69-C-1890, December 1970.

(3) Stemme, H.W., Lockheed-Georgia Co., Technical Report AFML-TR-73-49, Contract F33615-71-C-1682, April 1973.

(4) Summary Report, Air Force-Industry Formable Titanium Sheet Workshop, Dayton, Ohio, 5 June 1973.

2) Cold forming followed by mild restraint or hot size - aging at low temperatures would be an acceptable fabrication method which should decrease costs.

Another conclusion was that the volume of usage expected in the near future is not high for any one product form. The greatest inroads will be where elevated temperatures and/or corrosive environments are anticipated. The low initial volume for a given product form was not consistent with the requirement for volume production in cold strip and indicated that initially some hand mill production may be necessary. Prior experience with beta type Ti-13V-11Cr-3Al and Ti-8Mo-8V-2Fe-3Al alloys had shown that cold rolling gave better aged property uniformity from sheet to sheet than the hot roll processes. These two factors--1) an initially restricted market potential, and 2) the beneficial effects of cold rolling--led to incorporating the somewhat unusual hot plus cold roll approach.

The other conclusions drawn from the Workshop have generally been incorporated in the present program such as evaluation of fracture toughness, fatigue, weldability, etc. The weldability evaluation of the three alloys is being conducted at Wright Field and will be reported separately.

The results on Contract No. F33615-72-C-1696 had indicated the three alloys were adaptable to conventional consumable electrode vacuum melting using commercially available alloy and master alloy additions for small ingots. No unusual ingot homogeneity problems were found in ingots up to 40 lbs.

Mill processing of ingot to flat roll appeared practical based on similarities established for the three alloys to Ti-13V-11Cr-3Al and Ti-8Mo-8V-2Fe-3Al alloys which had been strip produced. These similarities were established in a series of laboratory experiments at known critical areas in the processing such as:

Hot Rolling Characteristics
Thermal and Mechanical Beta Phase Stability
Cold Rollability
Property Directionality

In the present investigation the plan was to make 0.050 and 0.100" thick flat roll product by each of the three methods:

1) Simulated strip
2) Hot plus cold roll
3) Hot roll

SECTION II

PHASE I

A. INGOT FORMULATION, MELTING AND HOMOGENEITY

The materials used in formulation of the 1800-lb ingots for the three alloys are shown in Table 1, along with analyses. These additions were weighed, blended and pressed to form 4" half octagonal x 12" long compacts. These compacts were weld joined to form two primary melting electrodes. After vacuum primary melting the two 14" diameter primary electrodes were joined by welding, inverted and vacuum melted into an 18" diameter furnace. These 14" and 18" diameter melting furnaces differ from conventional production furnaces in the U.S. only by being cooled by a liquid mixture of sodium and potassium (NaK).

Sampling of ingots for analyses was at top, middle, and bottom positions by trepanning and core drilling. These results are shown in Table 2, and generally good homogeneity was obtained for all except that the top ingot position had chromium higher than the normal formulation range shown at the right of the table for all three ingots. For the Ti-8V-7Cr-3Al-4Sn-1Zr alloy chromium was high by 0.2%, for the Ti-8V-4Cr-2Mo-2Fe-3Al alloy chromium was high by 0.4%, and for the Ti-15V-3Cr-3Al-3Sn by 0.1%. Additional chemistry samples were obtained from the outside of the forged sheet bar for the two Ti-8V-etc. compositions which come into the formulation range. The analytical results for these samples are shown in Table 3 and they are believed to be more representative of material chemistry than the original ingot analyses.

The only reasonable explanation for the high chromium content of the ingots appears to be spatter of high chromium metal from the molten pool to the outside of the crucible during the last portion of melting.

B. MILL PROCESSING

The forging schedule is shown in Table 4 along with recovery data. No unusual problems were observed and drafting pressures and scaling behavior were similar to the beta alloys, Ti-13V-11Cr-3Al and Ti-8Mo-8V-2Fe-3Al alloys.

TABLE 1

MATERIALS USED IN FORMULATION OF INGOT COMPOSITIONS

	Ti	85/15	Al	Cr	Sn	Zr	Mo-Al	Fe
V5029*	265	A-637	A-1	A-640	A-520	A-631	-	-
V5030*	265	A-604	A-1	A-640	-	-	A-639	A-518
V5031*	265	A-637	A-1	A-640	A-520	-	-	-

ANALYSIS OF MATERIALS

Ti - Lot 265		109Bhn - .071O_2 - .009N - .04Fe - .026C
85/15	A-637	82.5V - 15.7Al - .16O_2 - .057N - .52Fe - .018C - .36Si - .0019B
85/15	A-604	85.3V - 13.2Al - .237O_2 - .039N - .47Fe - .026C - .20Si - .0025B
Al	A-1	99.7Al - .005O_2 - .013N - .1Fe - .27Si - .002B
Cr	A-640	99.3Cr - .057O_2 - .029N - .29Fe - .03Mn
Sn	A-520	.13Fe - .005N - .003Si - .03Cu - .003Al
Zr	A-631	99.5Zr - .114O_2 - .004N - .076Fe
Mo-Al	A-639	52.9Mo - 42.2Al - 3.75Ti - .040O_2 - .013N - .14Fe - .43Si
Mo-Al	A-630	52.6Mo - 42.6Al - 4.22Ti - .072O_2 - .010N - .18Fe - .28Si
Fe	A-518	99.9Fe - .0028B

* Heat - alloy designations

V5029 Ti-8V-7Cr-3Al-4Sn-1Zr
V5030 Ti-8V-4Cr-2Mo-2Fe-3Al
V5031 Ti-15V-3Cr-3Al-3Sn

TABLE 2

CHEMISTRIES FOR FORMABLE SHEET INGOTS

Element	Analysis, Weight % For Position Indicated: T	M	B	Avg.	Formulation Range,%
V-5029 Ti-8V-7Cr-3Al-4Sn-1Zr					
V	8.0	8.0	8.1	8.0	7.5-8.5
Cr	7.7	6.6	6.9	6.8	6.5-7.5
Al	3.0	2.9	2.9	2.9	2.7-3.3
Sn	3.9	4.0	4.0	4.0	3.6-4.4
Zr	1.0	1.0	1.0	1.0	0.8-1.2
O_2	0.09	0.1	0.09	0.09	0.13 max.
N_2	0.016	0.016	0.017	0.016	---
Fe	0.14	0.13	0.14	0.14	---
V-5030 Ti-8V-4Cr-2Mo-2Fe-3Al					
V	8.0	7.8	7.7	7.8	7.5-8.5
Cr	4.8	3.9	3.9	4.0	3.6-4.4
Mo	1.8	1.8	1.8	1.8	1.8-2.2
Fe	2.3	2.0	2.0	2.1	1.8-2.2
Al	2.8	2.9	2.8	2.8	2.7-3.3
O_2	0.11	0.10	0.10	0.10	0.13 max.
N_2	0.016	0.014	0.015	0.015	---
V-5031 Ti-15V-3Cr-3Al-3Sn					
V	14.9	14.9	15.1	15.0	14-16
Cr	3.4	2.9	3.1	3.1	2.7-3.3
Al	2.9	2.9	3.0	2.9	2.7-3.3
Sn	3.1	3.1	3.1	3.1	2.7-3.3
O_2	0.11	0.11	0.12	0.11	0.13 max.
N_2	0.025	0.026	0.024	0.025	---
Fe	0.27	0.21	0.25	0.24	---

TABLE 3

CHEMICAL ANALYSES FOR FORGED SHEET BAR

Heat No.	Sheet Bar No.	Calculated Ingot Position	Weight Per cent of Element Indicated						
			V	Cr	Al	Sn	Zr	Mo	Fe
Ti-8V-7Cr-3Al-4Sn-1Zr									
V-5029	T crop	T-O center	8.0	7.0	3.0	3.9	1.0	-	-
"	T crop	T-O outside	7.9	6.8	3.0	3.8	1.0	-	-
"	9	T-4% "	8.1	7.1	2.9	3.9	1.0	-	-
"	8	T-11% "	8.1	6.8	2.9	3.9	1.0	-	-
"	7	T-18% "	8.2	6.8	2.9	3.9	1.0	-	-
"	6	T-27% "	8.0	6.8	2.8	3.8	1.0	-	-
"	6	T-27% center	7.8	6.7	2.8	3.8	1.0	-	-
Ti-8V-4Cr-2Mo-2Fe-3Al									
V-5030	T crop	T-O center	8.0	4.3	2.8	-	-	1.8	2.3
"	T crop	T-O outside	8.0	4.1	2.8	-	-	1.8	2.2
"	18	T-4% "	7.9	4.0	2.8	-	-	1.9	2.0
"	17	T-10.5% "	8.0	4.0	2.9	-	-	1.9	2.0
"	16	T-18% "	8.0	4.0	2.9	-	-	1.8	2.0
"	15	T-26% "	8.0	3.8	3.0	-	-	1.9	1.8
"	15	T-26% center	8.0	4.3	2.9	-	-	1.8	2.3
Ti-15V-3Cr-3Al-3Sn									
V-5031	T crop	center	15.0	3.0	2.9	3.0	-	-	-
"	B crop	center	15.0	3.0	2.9	3.0	-	-	-

TABLE 4

FORGING SCHEDULE AND RECOVERY FOR 1800-LB. INGOTS

1) Forge 18" diameter ingots to 7" x 16" x length at 2000F and square edges

2) Intermediate overall condition

3) Forge to 3-1/2" x 16" x length at 1750F and square edges

4) Preheat to 800F

5) Overall grind

6) Hand grind to remove defects

7) Ultrasonic test

Alloy	Ingot Weight, Lbs.	Conditioned Uncropped Slab Weight, Lbs.	Recovery %
Ti-8V-7Cr-3Al-4Sn-1Zr	1800	1672	92.9
Ti-8V-4Cr-2Mo-2Fe-3Al	1839	1650	89.7
Ti-15V-3Cr-3Al-3Sn	1835	1673	91.1

Generally, beta alloys show less tendency to cracking than alpha and alpha-beta alloys, but metal removal by grinding is more difficult for the betas.

The minor differences between recoveries for the three alloys are not believed significant. End losses were not detectably different after cropping and no pipe was found in the three slabs.

The cutting layout for the forged 3" thick x 16" wide sheet bars is shown in Figure 1 to approximate scale. The dashed vertical lines separate the materials according to the processing intended which is related to bar numbers as follows.

Code	Ga. Aim	
Cold Strip Process		
-02	0.050	Lab Simulated Strip
-03	0.100	" " "
-04	0.100	Sheet Simulated Strip
-05	0.050	" " "
Hot plus Cold		
-06	0.100	
-07	0.050	
Hot Roll		
-08	0.100	1750F rolled
-09	0.050	" "
-10	0.100	1850F rolled

A summary of the processing applied is given in Table 5. The simulation of strip by two methods was because sufficient material was not available to go to a Sendzimir mill where tension could be applied during rolling. The cold mills available for small lots where the conditions of high load and front and back tension could be applied during rolling are restricted in width to 6" and under. The 36" wide sheets were rolled on a four high cold mill without tension from starting hot band, nominal 0.17", gage to give sufficient width for all evaluation tests. The major difference in both these simulations from the conventional strip process was the necessity to hot cross roll the 16" wide sheet bar to 36+" wide. In conventional strip processing the non-unidirectional working applied is in spreading the forged slab from a width corresponding to ingot diameter to the width necessary to yield the finished strip width.

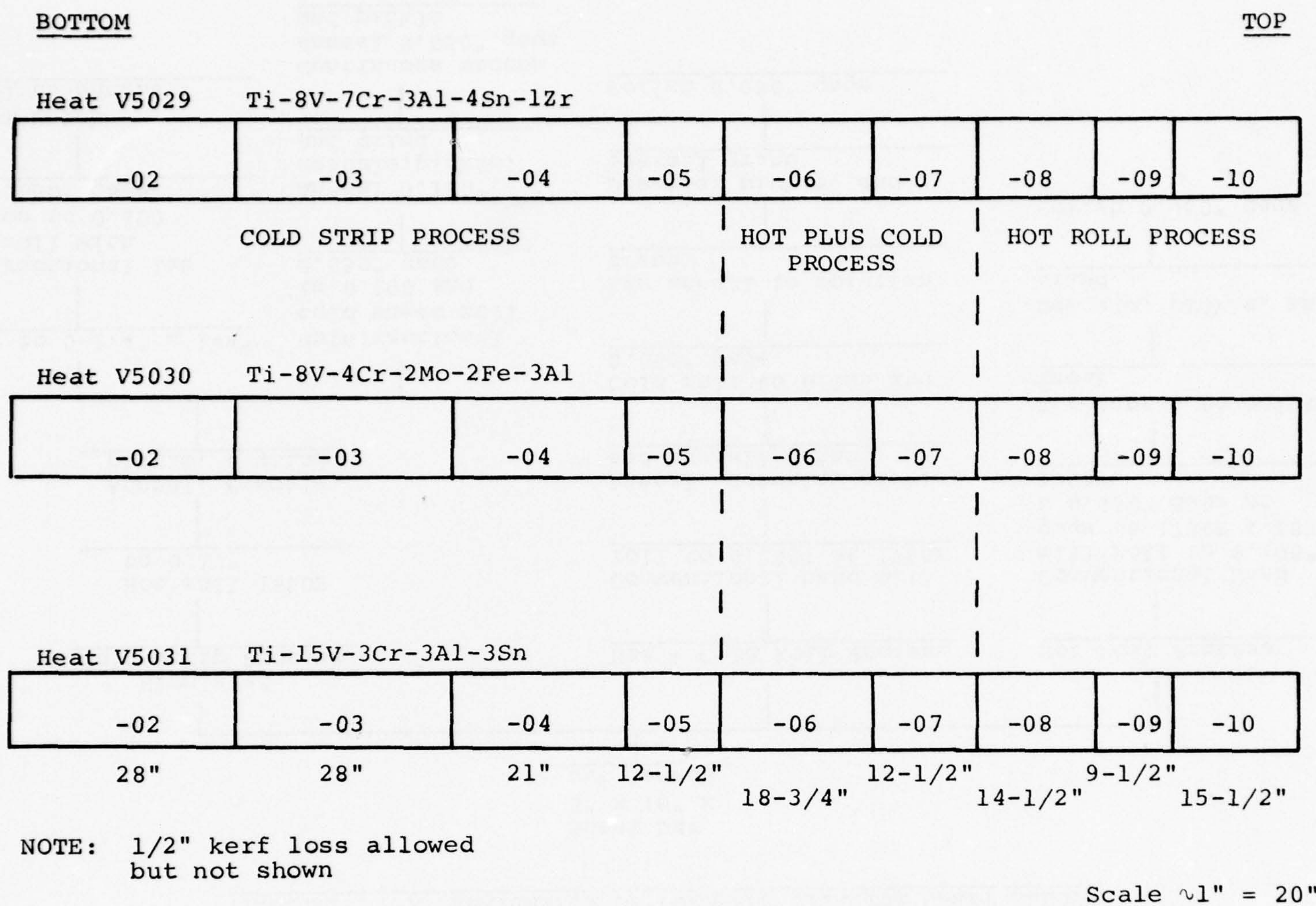


FIGURE 1. Cutting Layout for Sheet Bars

TABLE 5

FLOWSHEET FOR FABRICATION OF FORMABLE TITANIUM SHEET ALLOYS

Sheet bar
3" x 16" x
cut length

Simulated
Cold Strip Process

Hot roll 1850F
to 0.17"

Anneal, descale,
pickle, & grind

Shear to 5-1/4" x 144"

Unidirectional lab
cold roll with
tension to 0.100
and 0.050" gage

Vacuum batch
anneal as panels

Unidirectional
cold sheet roll
to 0.100 and
0.050" gage

Anneal 0.100",
descale,pickle,
and grind

Continuous vacuum
anneal 0.050" gage
and pickle

Hot + Cold Roll Process

Conventional hand mill
roll to 0.250" at 1750F

Anneal, descale, pickle,
and overall grind

Cold roll to 0.100 and
0.050" gage

Air anneal to solution
treat

Descale, pickle, and
overall grind

Polish 0.050" gage

Hot Roll Process

Conventional hand
mill roll to 0.100"
gage at 1750F & 1850F
& 0.050" Gage at
1750F

Air anneal to solution
treat

Descale, pickle, and
grind

Polish 0.050" gage

The processing detail for hot band equivalent is shown in Table 6. Cross rolling 16" to approximately 39" was at 1850F. The furnaces used for heating are roller hearth type with the first two zones gas fired and the third zone electric. Initial heating times varied from 70 to 120 minutes for the 3" thick slab. At 1850F the three alloys were softer than Ti-6Al-4V at 1700F. At the 1750F reheat temperature the three alloys were about the same or a little stiffer than Ti-6Al-4V at 1700F. This mill is not load instrumented so no more detailed information can be provided. Hot rolling behavior for the three alloys was comparable again to Ti-13V-11Cr-3Al and Ti-8Mo-8V-2Fe-3Al alloys.

The cold finish processing for laboratory and sheet simulated strip is shown in Table 7. In the laboratory simulated strip processing for 0.050" gage both the two-high and four-high configurations were tried. The gage aim could be met with both but within the load limits available the four-high rolls gave the best simulation of Sendzimir mill practice.

Comparison of rolling loads for 0.100" gage aim are shown in Figure 2 and for 0.050" gage aim in Figure 3. The Ti-8V-7Cr-3Al-4Sn-1Zr and Ti-8V-4Cr-2Mo-2Fe-3Al alloys required higher rolling loads and more roll passes to finish gage than the Ti-15V-3Cr-3Al-3Sn alloy. This difference would probably not be significant in terms of processing costs. The loads shown for one screw are half of the total mill load.

Hot rolling detail for the hot plus cold process is shown in Table 8. Breakdown and finish rolling were both at 1750F. Cold roll processing is shown in Table 9 and rolling data in Table 10. The rolling mill was a four-high sheet type. The intermediate anneal for the 0.050" gage aim material was used primarily because of a limitation imposed by the mill. The mill had just been overhauled prior to this rolling. The break-in period for rolling light gage material requires a number of sheets of the same composition to obtain proper adjustment and set-up and usually a number of sheets are lost due to crimping, pinching, etc. In this case only one sheet for each gage and alloy were available and the risk of loss did not appear justified.

Processing for the hot rolled sheet is shown in Table 11. Gage removal data for the grind and pickle operations is shown in Table 12 for all hot rolling. Generally there was little difference between these alloys or between these alloys and Ti-8Mo-8V-2Fe-3Al and Ti-13V-11Cr-3Al alloys in regard to gage removal required for cleanup.

TABLE 6

PROCESSING FOR HOT BAND FOR LABORATORY AND SHEET SIMULATED STRIP

Heat to 1850F

Roll 16" to width on roughing mill

Turn and roll to length at 0.30 to 0.35" gage

Reheat 1750F

Roll to 0.20 to 0.23" gage on finish mill

Reheat 1750F

Roll to 0.19 to 0.20" gage

Cut hydrogen samples and hold for release

Blast

Descale with KOH and pickle

Vacuum anneal 1350F-6hrs

Cut hydrogen samples and hold for release

Continuous anneal and pinch roll flatten *

Wet belt grind overall with hard back-up roll

Spot grind as necessary

Pickle, cleanup

Final inspect

*Anneals were 10 mins. at temperature with

Ti-8V-7Cr-3Al-4Sn-1Zr	at 1400F
Ti-8V-4Cr-2Mo-2Fe-3Al	at 1500F
Ti-15V-3Cr-3Al-3Sn	at 1450F

TABLE 7

PROCESSING FOR FINISH SIMULATED STRIP

Laboratory Simulated Strip

Shear 0.17" x 36" x length sheet to 5-1/4" wide x length

Attach stainless steel tails

Cold roll to 0.100" gage on 2 high mill with tension
Cold roll 0.050" gage on 4 high mill with tension
Remove tails and inspect

Cut strip to mult lengths required for testing

Vacuum anneal in cold wall furnace[1]
cooling rate to simulate production continuous vacuum anneal practice

Flash pickle in 15HNO_3 - 1.5 HF + rinse

Submit to machining

Sheet Simulated Strip

Roll 0.17" x 36" wide to gage at 96+" long on 4 high mill

Tail and continuous vacuum anneal 0.050" gage[1]

Flash pickle 0.050" gage - inspect + cut to tests
Air anneal 0.100" gage[2]
Caustic descale and cut hydrogen test
Overall wet belt grind (120 grit)

15 HNO_3 - 1.5 HF pickle
Inspect
Shear to test size and submit to machining

[1] Anneals used for lab strip and 0.050" gage sheet strip were:

Ti-8V-7Cr-3Al-4Sn-1Zr	1400F - 5 mins.
Ti-8V-4Cr-2Mo-2Fe-3Al	1500F - 5 mins.
Ti-15V-3Cr-3Al-3Sn	1450F - 5 mins.

[2] Anneals for 0.100" gage sheet strip were 10 mins.

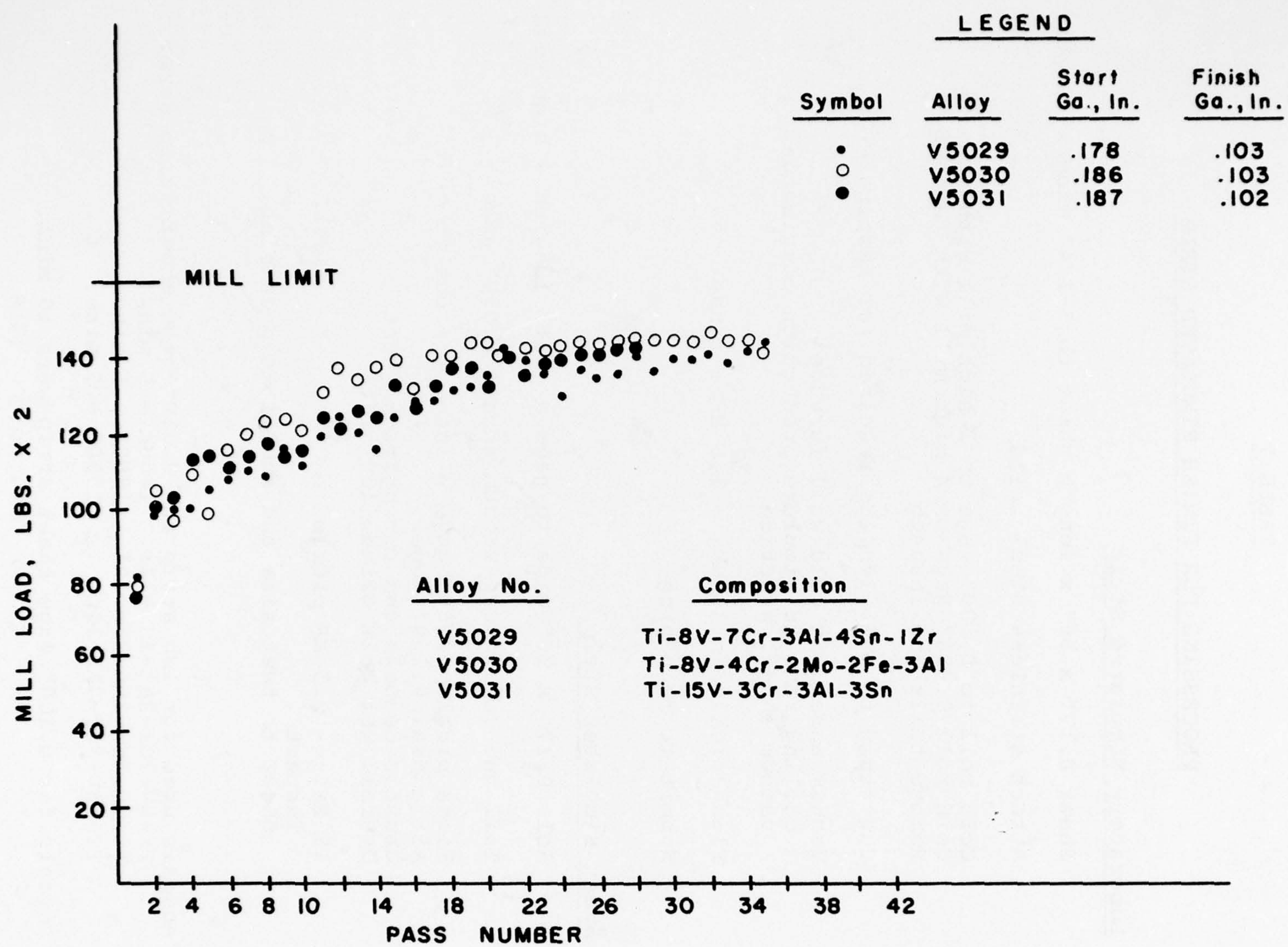


FIGURE 2. Rolling loads for three alloys using two-high rolls to 0.100" nominal gage coils.

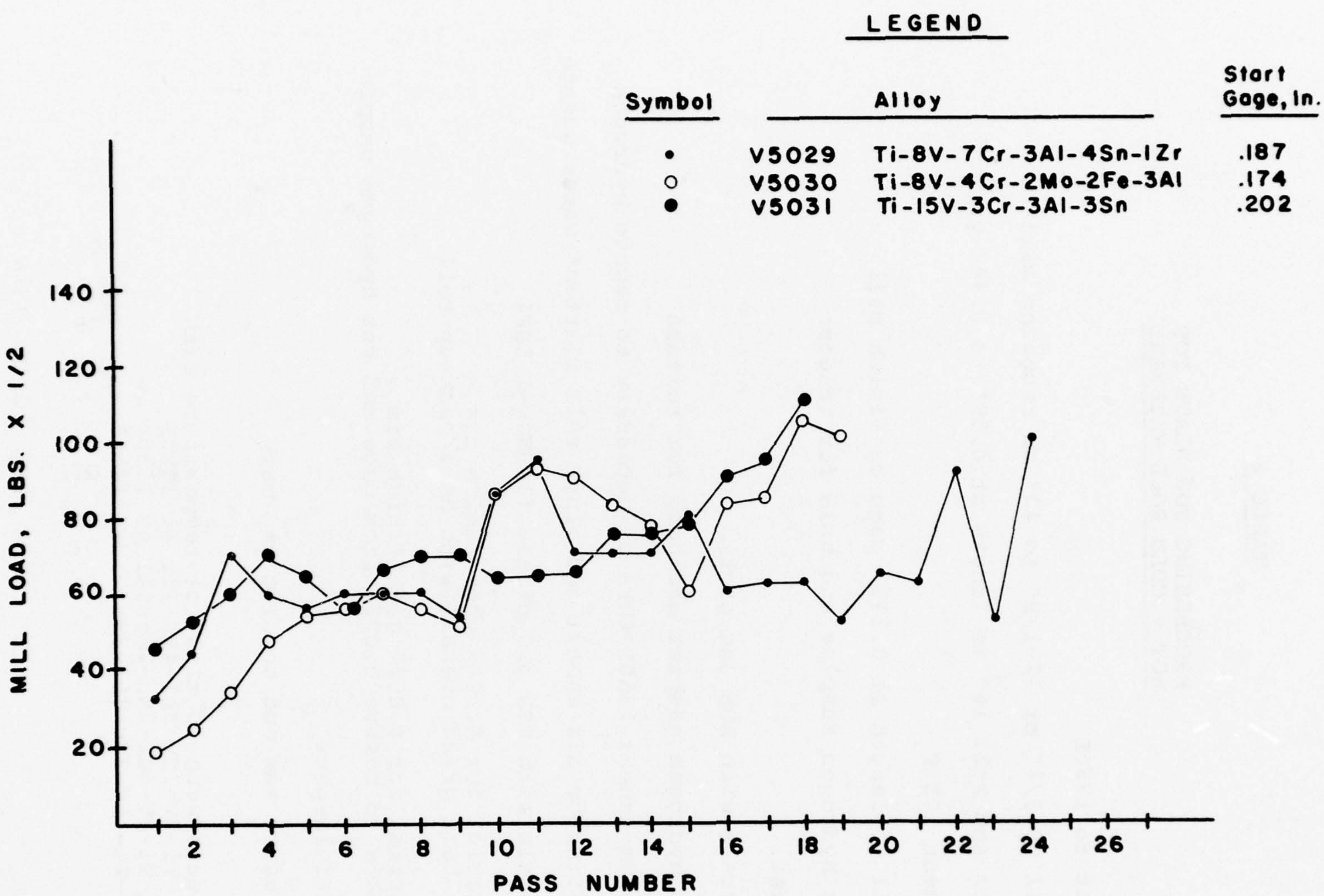


FIGURE 3. Rolling loads for three alloys using four-high rolls to 0.050" nominal gage coils.

TABLE 8

PROCESSING FOR PLATE FOR HOT + COLD ROLL MATERIAL

Heat to 1750F

Roll 18-3/4" or 12-1/2" to 42" on roughing mill

Turn and roll 16" to length at 0.39" to 0.44" gage

Reheat 1750F

Roll to length at 0.275" gage on finish mill

Cut hydrogen samples and hold for release

Blast

Descale with KOH and pickle

Cut hydrogen samples and hold for release

Vacuum anneal 1350F-6hrs as necessary to remove hydrogen

Continuous air anneal and pinch roll flatten* water quench

Descale with KOH and pickle (11HNO_3-1.5HF)

Material for 0.100" gage finish aim -
wet belt grind overall with hard back-up roll

Material for 0.050" gage finish aim -
pickle to remove 0.008" from gage and cut hydrogen sample

Final inspect

Abrasive saw cut to size and mark

*Anneals were 10 mins. at temperature with
Ti-8V-7Cr-3Al-4Sn-1Zr at 1400F
Ti-8V-4Cr-2Mo-2Fe-3Al at 1500F
Ti-15V-3Cr-3Al-3Sn at 1450F

TABLE 9

PROCESSING FOR FINISH OF HOT PLUS COLD ROLL SHEET

Roll 0.25" plate to nominal 0.100" gage and set aside 0.100" gage aim material

Intermediate anneal 0.050" gage aim sheet and pinch roll flatten*

Descale with KOH and pickle

Overall wet belt grind (120 grit), 0.004" off gage

Roll to 0.050" gage

Anneal 0.100 and 0.050" gage, pinch roll flatten and air cool both sides*

Wet belt grind overall (120 grit) 0.005" min. off gage

HNO_3-HF pickle 0.004" off gage

Shear to square

Inspect

* Intermediate and final anneals were 10 minutes:

Ti-8V-7Cr-3Al-4Sn-1Zr	at 1400F
Ti-8V-4Cr-2Mo-2Fe-3Al	at 1500F
Ti-15V-3Cr-3Al-3Sn	at 1450F

TABLE 10

COLD ROLLING DATA FOR
FOUR-HIGH SHEET ROLLING FULL SIZE SHEETS

Alloy No.[1]	Starting Ga., In.	Cold Rolled Ga., In.	Nbr. of Passes	% Reduction	Finish Gage Aim, In.
Hot plus Cold Sheet 0.100" Ga. Aim					
V5029	.264	.106	29	60	0.100
V5030	.266	.108	37	59	0.100
V5031	.254	.109	27	57	0.100
Hot plus Cold Sheet 0.050" Ga. Aim					
First Reduction					
V5029	.265	.104	17[2]	62	
V5030	.266	.099	17	63	
V5031	.264	.098	17	63	
Second Reduction after intermediate anneal, descale, pickle, & grind					
V5029	.100	.061	39	39	0.050
V5030	.092	.060	47	35	0.050
V5031	.093	.061	43	34	0.050

[1] V5029 - Ti-8V-7Cr-3Al-4Sn-1Zr
V5030 - Ti-8V-4Cr-2Mo-2Fe-3Al
V5031 - Ti-15V-3Cr-3Al-3Sn

[2] Cracked 8" from one end because of crimp

TABLE 11

PROCESSING DETAIL FOR HOT ROLL

Heat two bars each alloy to 1750F
Heat one bar each alloy to 1850F

Roll length of sheet bar to 39"

Turn and roll 16" width of sheet bar
Roughing of 1850F rolled bar complete at 0.31" gage

Reheat two bars each alloy to 1750F

Roll on finish mill

Cut hydrogen samples and hold for release

Flatten and solution anneal all 1450F-10min AC

Shear to size for weld pack

Weld in steel pack

Roll to length for 0.115" gage at 1750F for
0.100" finish gage

Roll to length for 0.070" gage at 1750F for
0.050" finish gage

Continuous anneal 1450F-10min. and air cool both sides

Caustic descale

Sample for hydrogen

Shear to square

Overall wet belt grind (120 grit)

15 HNO_3-1.5HF pickle

Shear to size

Final Inspect

TABLE 12

GAGE REMOVAL DATA FOR HOT ROLLED CONDITION AFTER ANNEALING

Heat No.	Alloy	Gage Aim, In.		Average[1] As Hot Rolled Ga., In.	Average[1] Ga. After Grind & Pickle	Gage Removal Grind & Pickle, In.
		As Hot Rolled	Final			
Simulated Strip Laboratory						
V-5029	Ti-8-7-3-4-1	.185	.050	.205	.183	.022
V-5030	Ti-8-4-2-2-3	.185	.050	.189	.167	.022
V-5031	Ti-15-3-3-3	.185	.050	.215	.196	.019
V-5029	Ti-8-7-3-4-1	.185	.100	.204	.173	.031
V-5030	Ti-8-4-2-2-3	.185	.100	.204	.181	.023
V-5031	Ti-15-3-3-3	.185	.100	.205	.185	.020
Simulated Strip Sheet Rolled						
V-5029	Ti-8-7-3-4-1	.185	.050	.192	.165	.027
V-5030	Ti-8-4-2-2-3	.185	.050	.183	.163	.020
V-5031	Ti-15-3-3-3	.185	.050	.192	.165	.027
V-5029	Ti-8-7-3-4-1	.185	.100	.194	.181	.013
V-5030	Ti-8-4-2-2-3	.185	.100	.192	.174	.018
V-5031	Ti-15-3-3-3	.185	.100	.192	.170	.022

-continued-

TABLE 12 - continued

Heat No.	Alloy	Gage Aim, In. As Hot Rolled	Gage Aim, In. Final	Average As Hot Rolled Ga., In.	Average Ga. After Grind & Pickle	Gage Removal Grind & Pickle, In.
Hot plus Cold						
V-5029	Ti-8-7-3-4-1	.275	.050	.279	.266	.013
V-5030	Ti-8-4-2-2-3	.275	.050	.281	.265	.016
V-5031	Ti-15-3-3-3	.275	.050	.279	.266	.013
V-5029	Ti-8-7-3-4-1	.275	.100	.275	.258	.020
V-5030	Ti-8-4-2-2-3	.275	.100	.275	.264	.011
V-5031	Ti-15-3-3-3	.275	.100	.278	.251	.027
Hot Rolled 1750F (Welded Pack)						
V-5029	Ti-8-7-3-4-1	.070	.050	.075[2]	.058	.017
V-5030	Ti-8-4-2-2-3	.070	.050	.073[2]	.055	.018
V-5031	Ti-15-3-3-3	.070	.050	.075[2]	.059	.016
V-5029	Ti-8-7-3-4-1	.115	.100	.107[2]	.090	.017
V-5030	Ti-8-4-2-2-3	.115	.100	.115[2]	.094	.021
V-5031	Ti-15-3-3-3	.115	.100	.117[2]	.093	.024
Hot Rolled 1850F (Welded Pack)						
V-5029	Ti-8-7-3-4-1	.115	.100	.127[2]	.107	.020
V-5030	Ti-8-4-2-2-3	.115	.100	.132[2]	.105	.027
V-5031	Ti-15-3-3-3	.115	.100	.128[2]	.106	.022

[1]Average of four readings near ends and edges.

[2]Gage readings from one end.

Beta alloys generally require more surface removal after heating in air than the alpha or alpha-beta alloys. Also gage removal by grinding is more difficult for the beta alloys. There was no indication that either of the present alloys would be more difficult or expensive to grind than presently available beta alloys. Acid pickling of beta alloys is more critical regarding hydrogen pickup than alpha or alpha-beta alloys which involves greater cost. However, there was no indication that these three alloys were more susceptible to hydrogen pickup than the other commercial beta alloys available. The gage ranges for all finished materials are shown in Table 13 along with an indication of shape or edge-center-edge thickness variation. The 0.17" gage hot band equivalent for the laboratory simulated strip is not shown because hot band is an intermediate and not a finished product. The 5-inch wide finished lab simulated strip had no detectable gage variation across the width.

Hydrogen and oxygen analyses were obtained for finished products as shown below:

		Analyses	
Alloy	Ga, In.	O_2%	H_2%
Laboratory Simulated Strip			
Ti-8V-7Cr-3Al-4Sn-1Zr	.050	.10	.0044
"	.100	.09	.0044
Ti-8V-4Cr-2Mo-2Fe-3Al	.050	.13	.0062
"	.100	.12	.0067
Ti-15V-3Cr-3Al-3Sn	.050	.13	.0047
"	.100	.12	.0070
Sheet Simulated Strip			
Ti-8V-7Cr-3Al-4Sn-1Zr	.050	.10	.0045
"	.100	.11	.0110
Ti-8V-4Cr-2Mo-2Fe-3Al	.050	.10	.0041
"	.100	.11	.0094
Ti-15V-3Cr-3Al-3Sn	.050	.12	.0030
"	.100	.12	.0121
Hot + Cold Rolled Sheet			
Ti-8V-7Cr-3Al-4Sn-1Zr	.050	.10	.0147
"	.100	.10	.0126
Ti-8V-4Cr-2Mo-2Fe-3Al	.050	.10	.0143
"	.100	.13	.0131
Ti-15V-3Cr-3Al-3Sn	.050	.10	.0165
"	.100	.12	.0113

TABLE 13

GAGE RANGE AND SHAPE FOR AS PRODUCED MATERIALS 36" x 96" SIZE

Alloy No.	Gage Range[1]	Shape
Sheet Simulated Strip (-04 & -05 tracers)		
V5029-05	.063 - .067	crown
V5030-05	.060 - .067	crown
V5031-05	.060 - .066	crown
V5029-04	.094 - .101	crown
V5030-04	.094 - .101	crown
V5031-04	.097 - .101	crown
Hot plus Cold (-06 & -07 tracers)		
V5029-06	.099 - .104	crown
V5030-06	.094 - .099	crown
V5031-06	.096 - .105	crown
Hot Rolled 1750F (-08 & -09 tracers)		
V5029-09	.057 - .059	crown
V5030-09	.052 - .055	crown
V5031-09	.058 - .060	crown
V5029-08	.088 - .091	crown
V5030-08	.093 - .097	crown
V5031-08	.092 - .096	crown
Hot Rolled 1850F (-10 tracer)		
V5029-10	.103 - .108	one heavy edge to crown
V5030-10	.101 - .105	crown
V5031-10	.105 - .107	crown

[1]Nine readings taken at edge, center, edge, end, mid length, & end

SECTION III

PHASE II

A. MECHANICAL PROPERTY EVALUATION

The as produced material was evaluated for tensile, bend and microstructure since these were the first materials made of the three alloys using conventional production equipment. Aging studies were then made on all products of the three alloys using 950, 1050, and 1150F temperatures and times of 2, 4, 8, and 16 hours. One aging treatment was selected for each alloy and condition for more extensive evaluation using the following tests:

- Fracture toughness
- Notched fatigue
- Fatigue crack propagation
- Compression
- Precision modulus
- Pole figure determinations
- Phase identification

1. Evaluation of As Produced Material

Tensile and bend results for all conditions oi the three alloys are shown in Table 14. Tensile and yield strengths were lower for V5031, the Ti-15V-3Cr-3Al-3Sn alloy, in all conditions than the V5029, Ti-8V-7Cr-3Al-4Sn-1Zr, or the V5030, Ti-8V-4Cr-2Mo-2Fe-3Al alloys. Bend R/t values for all alloys and conditions were larger for all materials than for the best values obtained on the laboratory material from the prior contract[1] indicating lower ductility for the present materials. The bend failures for the laboratory simulated strip were continuous across the width of the sample but the hot rolled material had the appearance of short cracks originating at the grain boundaries and revealed by the heavy "orange peel" pattern. This "orange peel" surface pattern was of the type associated with large grains. All hot rolled material was considered to fail bend test at radii shown because grain boundary sliding could not be differentiated from grain separation.

TABLE 14

AS PRODUCED TENSILE AND BEND PROPERTIES

Alloy No. *	Nominal Ga., In.	Anneal Temp, F	Anneal Time, Mins.	Test Dir.	Tensile Properties UTS, Ksi	YS, Ksi	El, %	Bend R/t 20X[1] Pass	Fail
1) Simulated Strip - Lab Rolled - Batch Vacuum Annealed									
V5029	.050	1400	5	L	125	122	16	-	-
"	"	"	5	T	126	124	22	4.0	3.6
V5030	.050	1500	5	L	122	120	20	-	-
"	"	"	5	T	126	122	20	4.0	3.6
V5031	.050	1450	5	L	115	112	17	-	-
"	"	"	5	T	116	113	22	3.6	3.2
V5029	.100	1400	5	L	127	123	21	-	-
"	"	"	5	T	133	127	17	-	5.0
V5030	.100	1500	5	L	124	120	19	-	brittle
"	"	"	5	T	127	124	19	5.0	3.8
V5031	.100	1450	5	L	113	111	22	-	-
"	"	"	5	T	119	116	19	5.0	3.8
Simulated Strip - Sheet Rolled - Continuous Vacuum Annealed and Pickled									
V5029	.050	1400	6	L	123	119	23	-	-
"	"	"	6	T	126	125	20	3.2	2.5 OP
V5030	.050	1500	6	L	121	119	23	-	-
"	"	"	6	T	122	118	22	2.5[2]	2.5[2]
V5031	.050	1450	6	L	109	106	25	-	-
"	"	"	6	T	112	109	23	2.5	-

-continued-

TABLE 14 - continued

Alloy No. *	Nominal Ga., In.	Anneal Temp, F	Anneal Time, Mins.	Test Dir.	Tensile Properties UTS, Ksi	Tensile Properties YS, Ksi	Tensile Properties El, %	Bend R/t 20X[1] Pass	Bend R/t 20X[1] Fail
Simulated Strip - Sheet Rolled - Air Annealed, Ground and Pickled									
V5029	.100	1400	10	L	124	119	21	-	-
"	"	"	10	T	128	124	19	3.2	2.5
V5030	.100	1500	10	L	120	116	24	-	-
"	"	"	10	T	121	118	23	2.5 OP	-
V5031	.100	1450	10	L	113	108	23	-	-
"	"	"	10	T	115	112	12[3]	3.1	2.5
2) Hot plus Cold									
V5029	.050	1400	10	L	127	123	21	-	-
"	"	"	10	T	129	126	20	2.0	-
V5030	.050	1500	10	L	121	117	24	-	-
"	"	"	10	T	123	119	21	2.1	-
V5031	.050	1450	10	L	111	107	24	-	-
"	"	"	10	T	113	109	23	2.1	-
V5029	.100	1400	10	L	121	119	23	-	-
"	"	"	10	T	123	119	22	2.5	-
V5030	.100	1500	10	L	124	119	19	-	-
"	"	"	10	T	128	124	17	-	3.2
V5031	.100	1450	10	L	110	106	24	-	-
"	"	"	10	T	112	109	24	2.5	-

TABLE 14 - continued

Alloy No. *	Nominal Ga., In.	Anneal Temp, F	Anneal Time, Mins.	Test Dir.	Tensile Properties UTS, Ksi	YS, Ksi	El, %	Bend R/t 20X[1] Pass	Fail
3) **Hot Rolled 1750F**									
V5029	.050	1400	20	L	126	122	17	-	-
"	"	"	20	T	129	125	13	-	3.0 OP
V5030	.050	1500	20	L	121	119	22	-	-
"	"	"	20	T	125	123	19	-	3.0 OP[4]
V5031	.050	1450	20	L	109	106	23	-	-
"	"	"	20	T	114	110	18	-	3.0 OP[4]
V5029	.100	1400	20	L	124	120	19	-	-
"	"	"	20	T	129	125	16	-	2.8 brittle
V5030	.100	1500	20	L	121	117	22	-	-
"	"	"	20	T	124	121	19	-	3.0 OP[4]
V5031	.100	1450	20	L	111	107	21	-	-
"	"	"	20	T	115	112	18	-	3.0 OP[4]
Hot Rolled 1850F									
V5029	.100	1400	20	L	124	120	23	-	-
"	"	"	20	T	129	125	16	-	3.0 OP[4]
V5030	.100	1500	20	L	121	118	20	-	-
"	"	"	20	T	125	-	19	-	3.0 OP[4]
V5031	.100	1450	20	L	110	108	23	-	-
"	"	"	20	T	114	112	23	-	3.0 OP[4]

-continued-

TABLE 14 - continued

[1]Tests conducted on both surfaces. "Brittle" indicates sample fractured on bending. OP - Deformed area had coarse, grainy appearance. Where failure indicated grains had separated to form a discontinuous cracked appearance.

[2]One side passed 2.5, other side failed 2.5.

[3]Fractured near gage mark.

[4]Fail by grain boundary sliding to give crack appearance which could not readily be distinguished from base metal failure. For this reason none could be rated as passing.

*V5029	Ti-8V-7Cr-3Al-4Sn-1Zr
V5030	Ti-8V-4Cr-2Mo-2Fe-3Al
V5031	Ti-15V-3Cr-3Al-3Sn

Surface contamination and/or incomplete anneal were suspect factors and were checked for the strip and hot rolled conditions with the results shown in Table 15. The laboratory simulated strip showed incomplete anneal as did the sheet simulated strip for the V5029, Ti-8V-7Cr-3Al-4Sn-1Zr at 0.050 and 0.100" gage. The bend ductility for the hot rolled conditions did not change appreciably with either surface removal or a higher temperature anneal because of the orange peel effect.

Tensile strengths determined for the higher temperature annealed conditions did not vary appreciably for those for the as produced condition. Ideally, the annealing conditions would have been determined separately for each alloy, gage, and condition but this procedure would have been too time consuming for the scope of the present investigation. More attention should be given this factor to obtain optimization for formability in future work. In the present study annealing temperatures and times were based on results of the prior study(1) with a judgement allowance for heating rates in various production furnaces.

Microstructures for the as received materials are shown in Figures 4 through 12. The annealing treatments shown are the same as for the tensile and bend properties in Table 14. The 0.050" gage strip photomicrographs in Figure 4 show essentially complete recrystallization. The 0.100" gage photomicrographs in Figure 5 show less complete recrystallization than at 0.050" gage particularly for the Ti-8V-7Cr-3Al-4Sn-1Zr and Ti-15V-3Cr-3Al-3Sn alloys. The dark grains in the Ti-15V-3Cr-3Al-3Sn photomicrograph may indicate incomplete solution of alpha phase, but the low strengths and high elongation values in Table 14 suggest other possibilities. Repeated polishing and etching have had little effect on this staining which indicates the possibility of an unresolved defect type structure in unrecrystallized material.

The microstructures for the 0.050" gage simulated strip sheet rolled, Figure 6, are comparable to Figure 4. The semicontinuous dark lines which appear superimposed on the recrystallized structure for the Ti-8V-7Cr-3Al-4Sn-1Zr alloy in Figure 6 were present to some degree for most conditions of this alloy with cold rolling (see also Figures 4, 5, 7, and 8).

TABLE 15

EXAMINATION OF TRANSVERSE BEND TEST RESULTS

	Alloy No.	Nominal Ga., In.	As Produced Bend R/t, 20X Passed	As Produced plus Re-Pickled Bend R/t, 20X Passed	Re-Annealed & Re-Pickled Bend R/t, 20X Passed	Anneal Temp, °F	Anneal Time, Mins.
1)	Simulated Strip - Lab Rolled - Batch Vacuum Annealed						
	V5029	0.050	4.0	4.0	2.1	1500	6
	V5030	"	4.0	4.0	2.1	1650	6
	V5031	"	3.6	3.6	2.1	1500	6
	V5029	0.100	>5.0	>5.0	2.5	1500	6
	V5030	"	5.0	5.0	2.5	1650	6
	V5031	"	5.0	5.0	2.5	1500	6
2)	Simulated Strip - Sheet Rolled - Continuous Vacuum Annealed and Pickled						
	V5029	0.050	3.2	3.2	2.7	1500	6
	V5030	"	2.5	2.5	-	-	-
	V5031	"	2.5	2.5	-	-	-
	V5029	0.100	3.2	3.1	2.0	1500	6
	V5030	"	2.5 L.O.P.[1]	2.5	-	-	-
	V5031	"	3.1	3.1	2.0	1500	6
3)	Hot Rolled, 1750°F						
	V5029	0.050	>3.0 H.O.P.[2]	>3.4 H.O.P.	3.4 H.O.P.	1650	6
	V5030	"	>3.0 H.O.P.	>2.5 H.O.P.	3.0 H.O.P.	1650	6
	V5031	"	>3.0 H.O.P.	3.1 H.O.P.	-	-	-

-continued-

TABLE 15 - continued

	Alloy No.	Nominal Ga., In.	As Produced Bend R/t, 20X Passed	As Produced plus Re-Pickled Bend R/t, 20X Passed	Re-Annealed & Re-Pickled Bend R/t, 20X Passed	Anneal Temp, °F	Anneal Time, Mins.
3)	Hot Rolled, 1750°F - continued						
	V5029	0.100	>2.8 brittle[3]	>3.7 H.O.P.	-	-	-
	V5030	"	>3.0 H.O.P.	2.6 H.O.P.	-	-	-
	V5031	"	>3.0 H.O.P.	2.6 H.O.P.	3.1 H.O.P.	1650	6
4)	Hot Rolled, 1850°F						
	V5029	0.100	>3.0 H.O.P.	2.8 H.O.P.	3.1 H.O.P.	1650	6
	V5030	"	>3.0 H.O.P.	3.7 H.O.P.	-	-	-
	V5031	"	>3.0 H.O.P.	2.8 H.O.P.	-	-	-

[1]L.O.P. designates light orange peel condition

[2]H.O.P. designates heavy orange peel condition

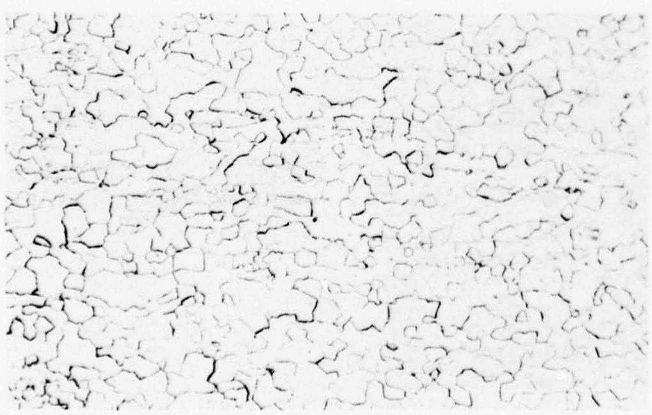
[3]Brittle - sample failed completely by fracture

Ti-8V-7Cr-3Al-4Sn-1Zr
Vacuum Batch Annealed
1400°F - 5 min.

75-5A V5029 100X

Ti-8V-4Cr-2Mo-2Fe-3Al
Vacuum Batch Annealed
1500°F - 5 min.

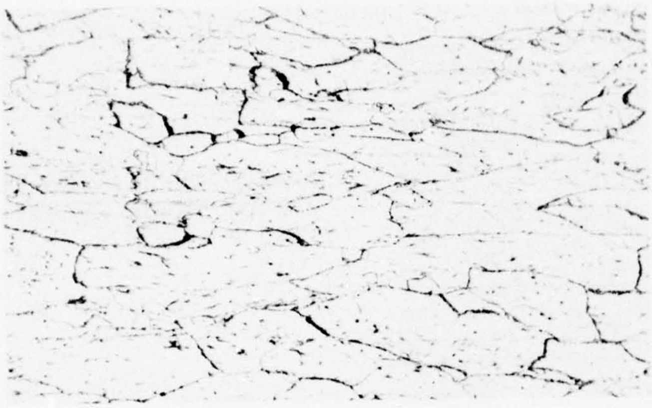
75-5B V5030 100X



Ti-15V-3Cr-3Al-3Sn
Vacuum Batch Annealed
1450°F - 5 min.

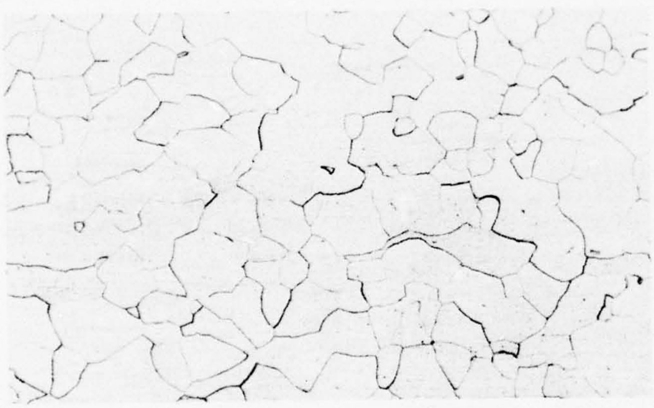
75-5C V5031 100X

FIGURE 4. Microstructures for 0.050" Gage Lab Simulated Strip



Ti-8V-7Cr-3Al-4Sn-1Zr
Vacuum Batch Annealed
1400°F - 5 min.

75-5D V5029 100X



Ti-8V-4Cr-2Mo-2Fe-3Al
Vacuum Batch Annealed
1500°F - 5 min.

75-5E V5030 100X

Ti-15V-3Cr-3Al-3Sn
Vacuum Batch Annealed
1450°F - 5 min.

75-5F V5031 100X

FIGURE 5. Microstructures for 0.100" Gage Lab Simulated Strip

Ti-8V-7Cr-3Al-4Sn-1Zr
Continuous Vacuum
Annealed 1400°F - 5min.

75-5J V5029 100X

Ti-8V-4Cr-2Mo-2Fe-3Al
Continuous Vacuum
Annealed 1500°F - 5min.

75-5K V5030 100X

Ti-15V-3Cr-3Al-3Sn
Continuous Vacuum
Annealed 1450°F - 5min.

75-5L V5031 100X

FIGURE 6. Microstructures for 0.050" Gage Sheet Simulated Strip

Ti-8V-7Cr-3Al-4Sn-1Zr
Air Annealed
1400°F - 10 min.

75-5G V5029 100X

Ti-8V-4Cr-2Mo-2Fe-3Al
Air Annealed
1500°F - 10 min.

75-5H V5030 100X

Ti-15V-3Cr-3Al-3Sn
Air Annealed
1450°F - 10 min.

75-5I V5031 100X

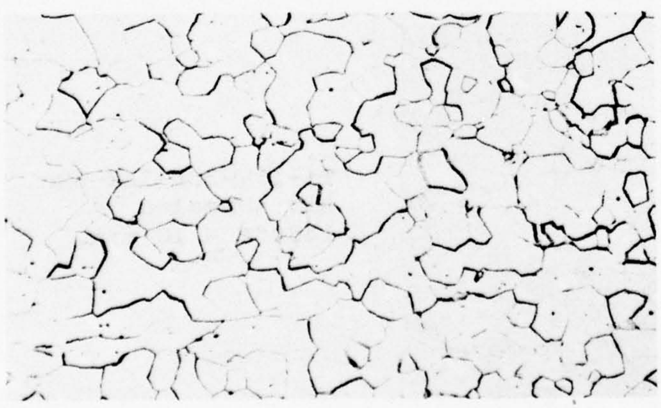
FIGURE 7. Microstructures for 0.100" Gage Sheet Simulated Strip

Ti-8V-7Cr-3Al-4Sn-1Zr
Air Annealed
1400°F - 10 min.

75-5M V5029 100X

Ti-8V-4Cr-2Mo-2Fe-3Al
Air Annealed
1500°F - 10 min.

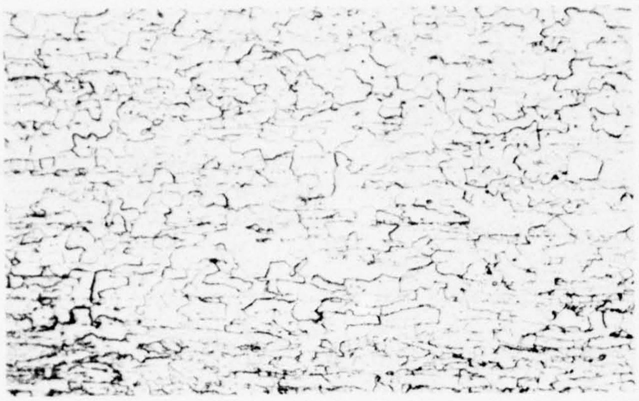
75-5N V5030 100X



Ti-15V-3Cr-3Al-3Sn
Air Annealed
1450°F - 10 min.

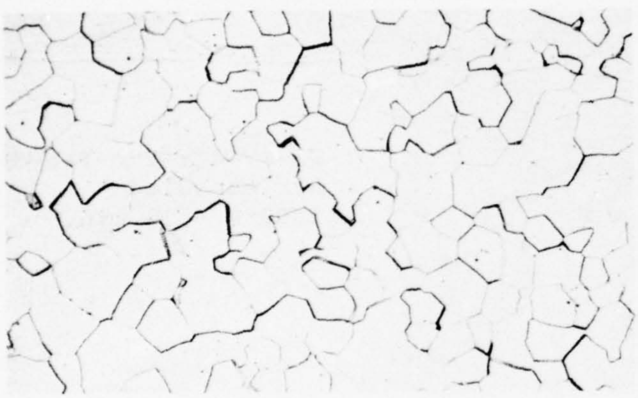
75-5O V5031 100X

FIGURE 8. Microstructures for 0.100" Gage Hot plus Cold Rolled



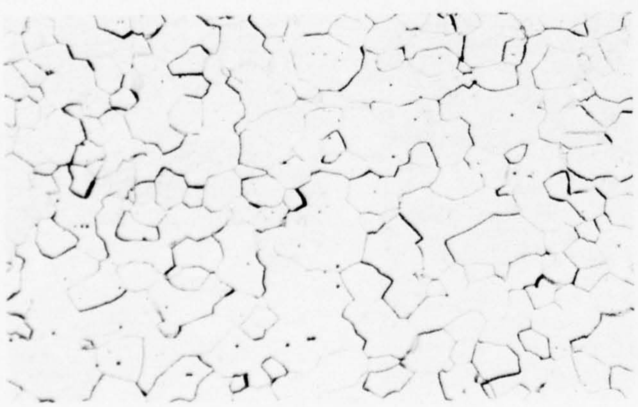
Ti-8V-7Cr-3Al-4Sn-1Zr
Air Annealed
1400°F - 10 min.

75-16A V5029 100X



Ti-8V-4Cr-2Mo-2Fe-3Al
Air Annealed
1500°F - 10 min.

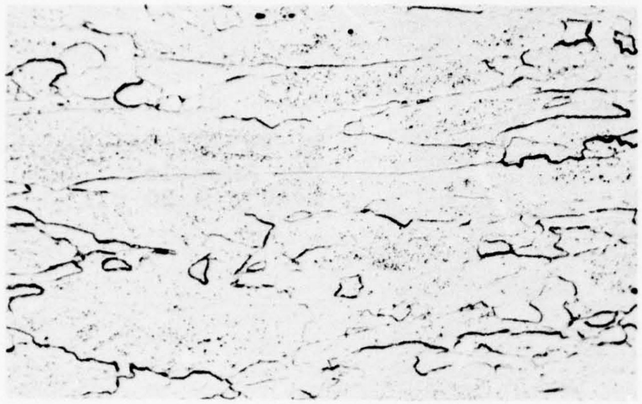
75-16B V5030 100X



Ti-15V-3Cr-3Al-3Sn
Air Annealed
1450°F - 10 min.

75-16C V5031 100X

FIGURE 9. Microstructures for 0.050" Gage Hot plus Cold Rolled

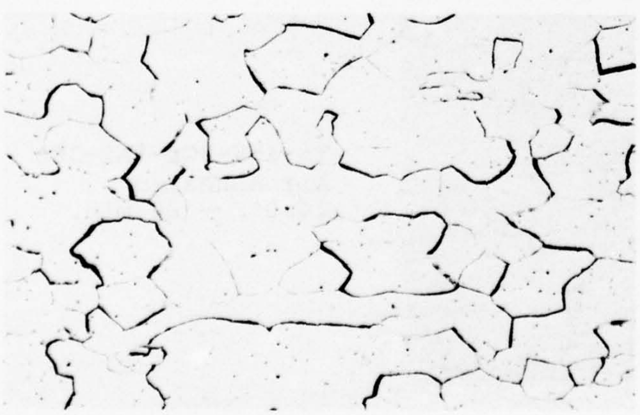


Ti-8V-7Cr-3Al-4Sn-1Zr
Air Annealed
1400°F - 20 min.

75-5V V5029 100X

Ti-8V-4Cr-2Mo-2Fe-3Al
Air Annealed
1500°F - 20 min.

75-5W V5030 100X



Ti-15V-3Cr-3Al-3Sn
Air Annealed
1450°F - 20 min.

75-5X V5031 100X

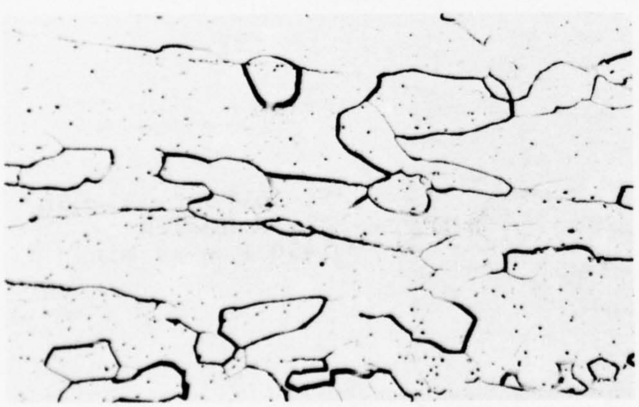
FIGURE 10. Microstructures for 0.050" Gage Hot Rolled 1750F

Ti-8V-7Cr-3Al-4Sn-1Zr
Air Annealed
1400°F - 20 min.

75-5S V5029 100X

Ti-8V-4Cr-2Mo-2Fe-3Al
Air Annealed
1500°F - 20 min.

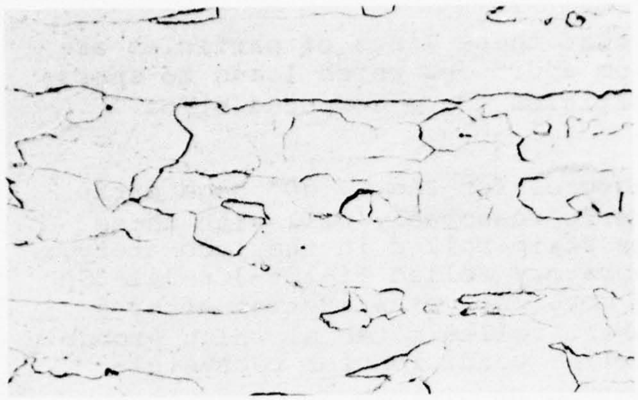
75-5T V5030 100X



Ti-15V-3Cr-3Al-3Sn
Air Annealed
1450°F - 20 min.

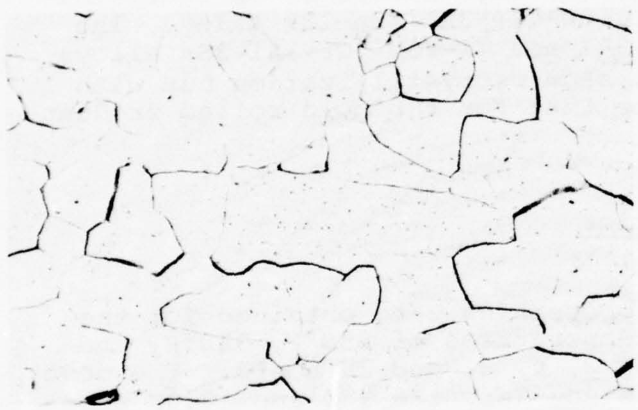
75-5U V5031 100X

FIGURE 11. Microstructures for 0.100" Gage Hot Rolled 1750F



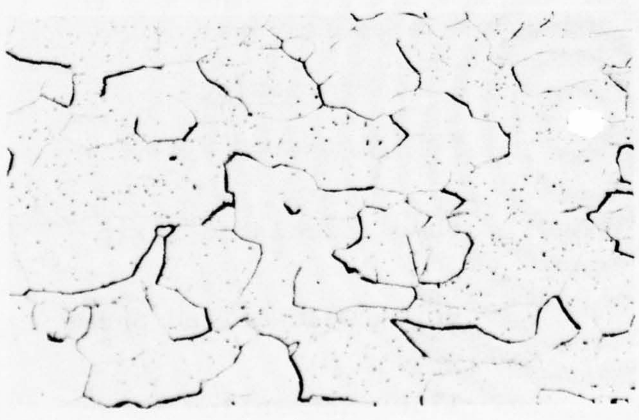
Ti-8V-7Cr-3Al-4Sn-1Zr
Air Annealed
1400°F - 20 min.

75-5Y V5029 100X



Ti-8V-4Cr-2Mo-2Fe-3Al
Air Annealed
1500°F - 20 min.

75-5Z V5030 100X



Ti-15V-3Cr-3Al-3Sn
Air Annealed
1450°F - 20 min.

75-5AA V5031 100X

FIGURE 12. Microstructures for 0.100" Gage Hot Rolled 1850F

There is evidence that these lines of particles are related to zirconium additions which leads to speculation that the particles are a compound(s) of zirconium.[5]

The microstructures for the 0.100" gage strip sheet, Figure 7, agree reasonably well with those for the 0.100" gage strip rolled in the laboratory, Figure 5. The laboratory rolled Ti-15V-3Cr-3Al-3Sn alloy material had more recrystallization after 5 minutes than the sheet rolled material which probably reflects the borderline condition for recrystallization.

The microstructures for the hot rolled condition, Figures 10, 11, and 12, show little or no recrystallization for the Ti-8V-7Cr-3Al-4Sn-1Zr alloy. The Ti-8V-4Cr-2Mo-2Fe-3Al and Ti-15V-3Cr-3Al-3Sn alloys are comparable and show recrystallization but with a larger grain size than for the cold rolled product.

2. Aging Characteristics

Aged tensile properties were obtained for the 27 conditions at temperatures of 850°F, 950°F, and 1050°F for times of 2, 4, 8, and 16 hours. The most pertinent to this study were the 950 and 1050F aged properties which are shown in Figures 13 through 18. In these figures processing and gages are indicated by tracer numbers for maximum clarity. The key to the tracer numbers and gages is as follows:

Tracer No.	Ga.,In.	Processing
02	.05	Lab Simulated Strip
03	.10	" " "
04	.10	Sheet Simulated Strip
05	.05	" " "
06	.10	Hot + Cold Rolled Sheet
07	.05	" " " "
08	.10	1750F Hot Rolled Sheet
09	.05	" " " "
10	.10	1850F Hot Rolled Sheet

(5) Private communication from Mr. J. A. Hall.

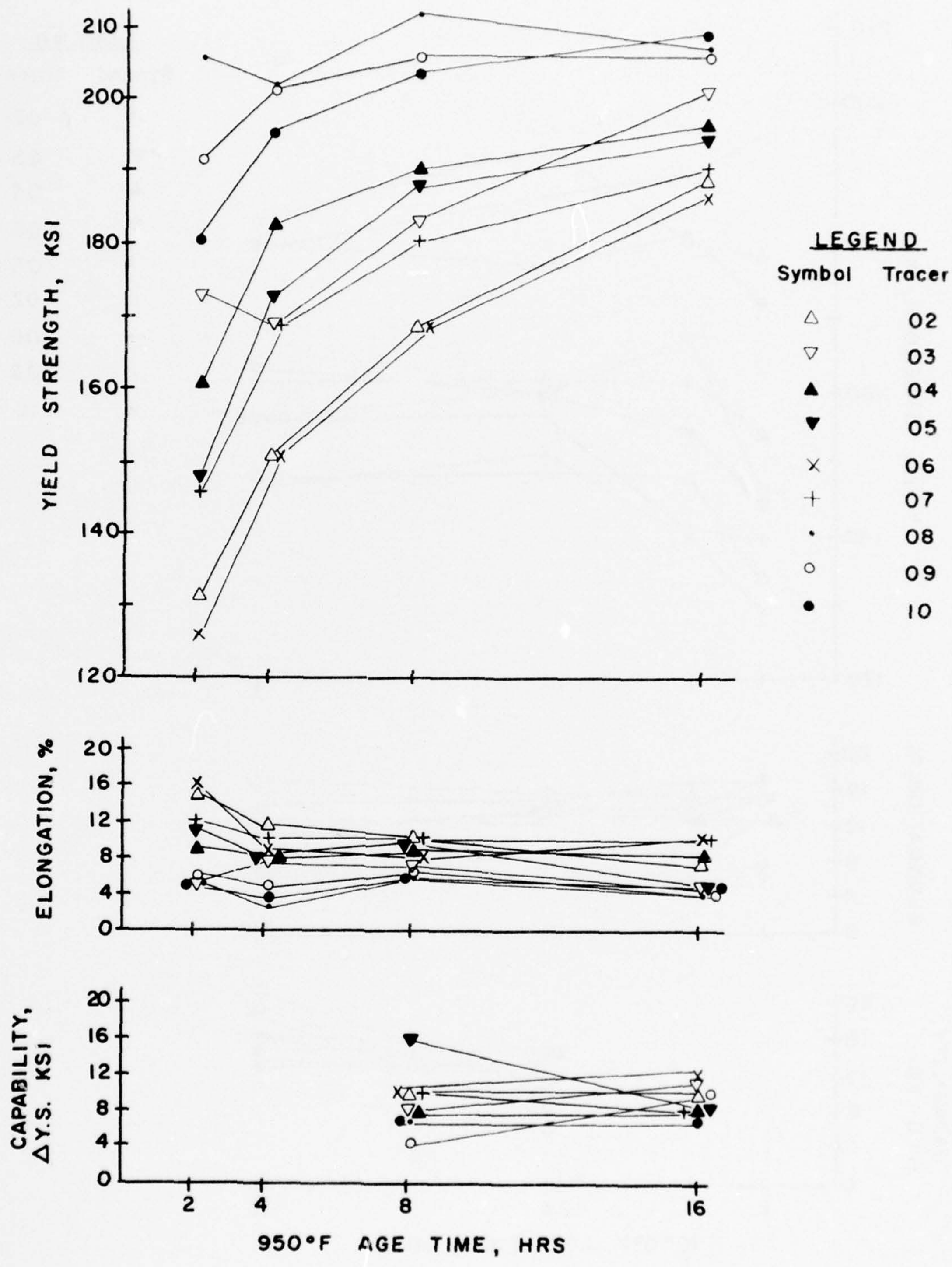


FIGURE 13. Ti-8V-7Cr-3Al-4Sn-1Zr Alloy 950°F Aged Yield Strength, Elongation, and Process Capability

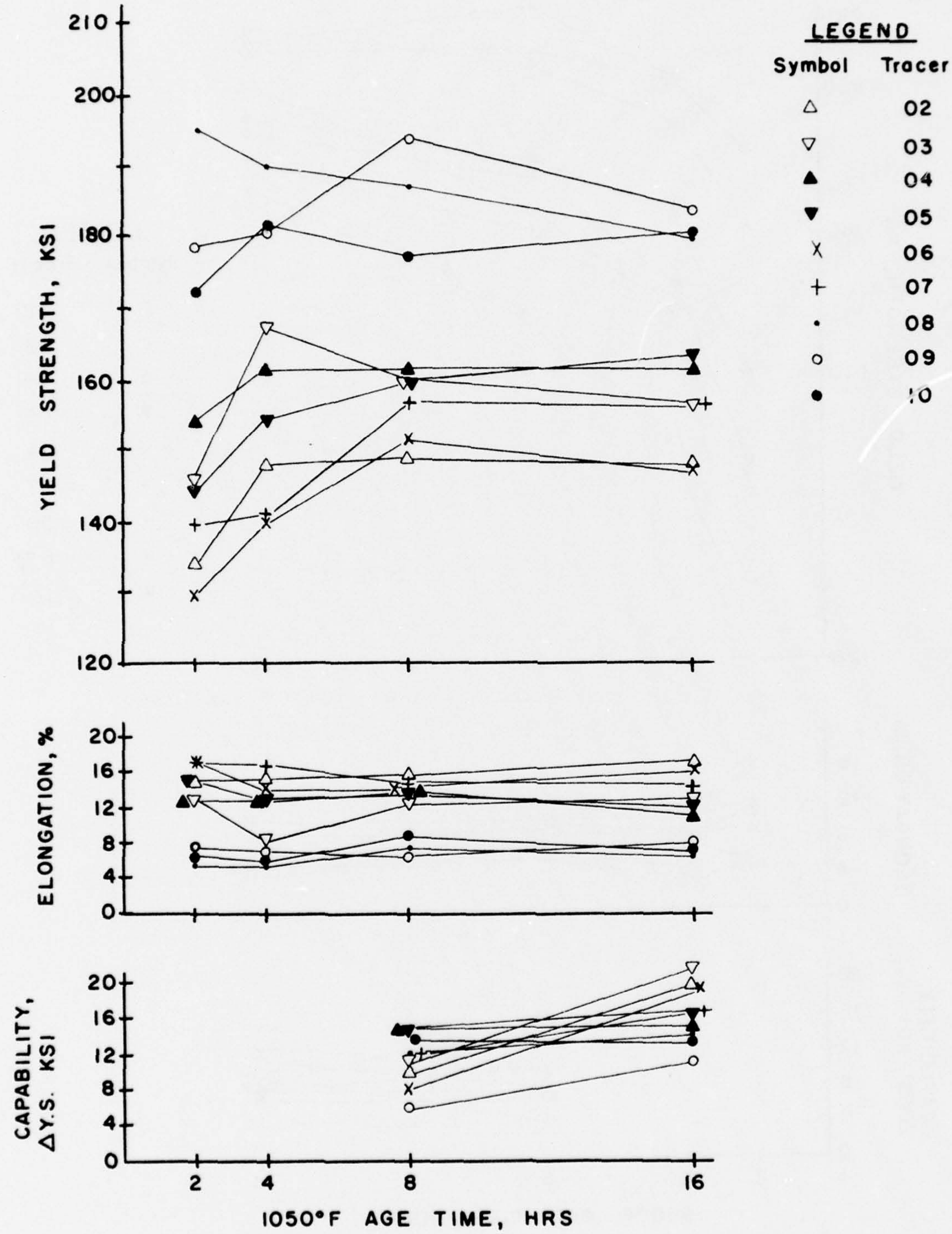


FIGURE 14. Ti-8V-7Cr-3Al-4Sn-1Zr Alloy 1050°F Aged Yield Strength, Elongation, and Process Capability

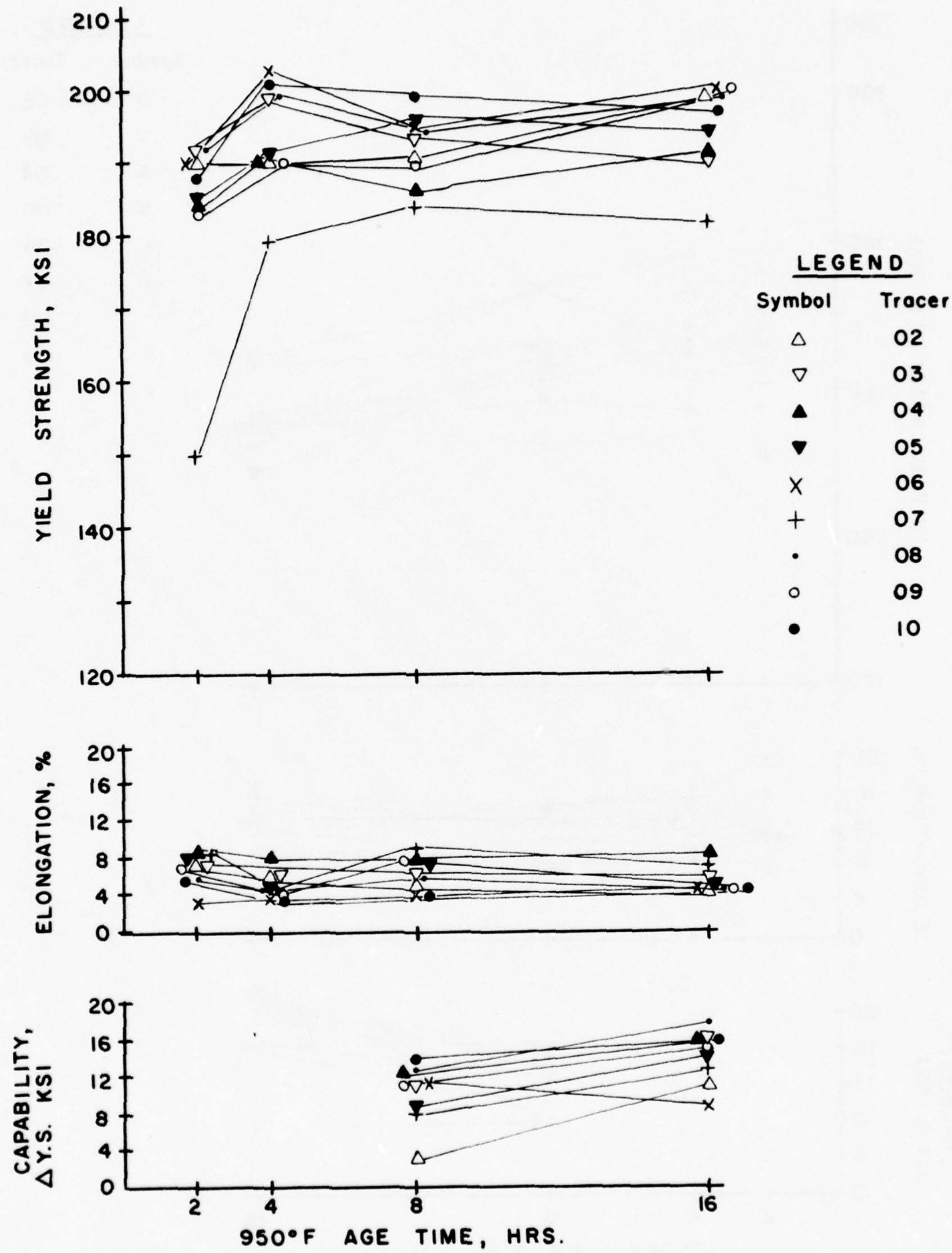


FIGURE 15. Ti-8V-4Cr-2Mo-2Fe-3Al Alloy 950°F Aged Yield Strength, Elongation, and Process Capability

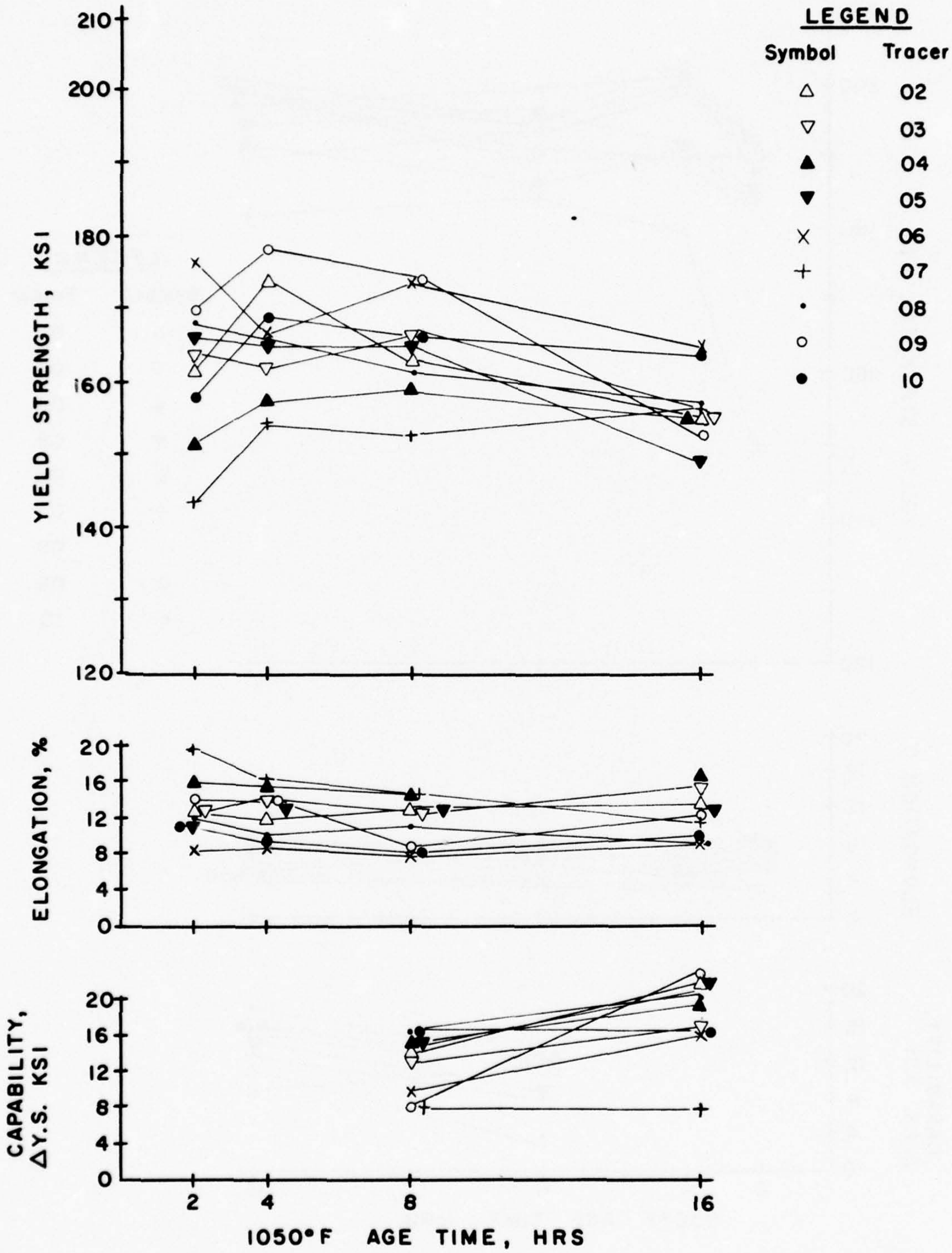


FIGURE 16. Ti-8V-4Cr-2Mo-2Fe-3Al Alloy 1050°F Aged Yield Strength, Elongation, and Process Capability

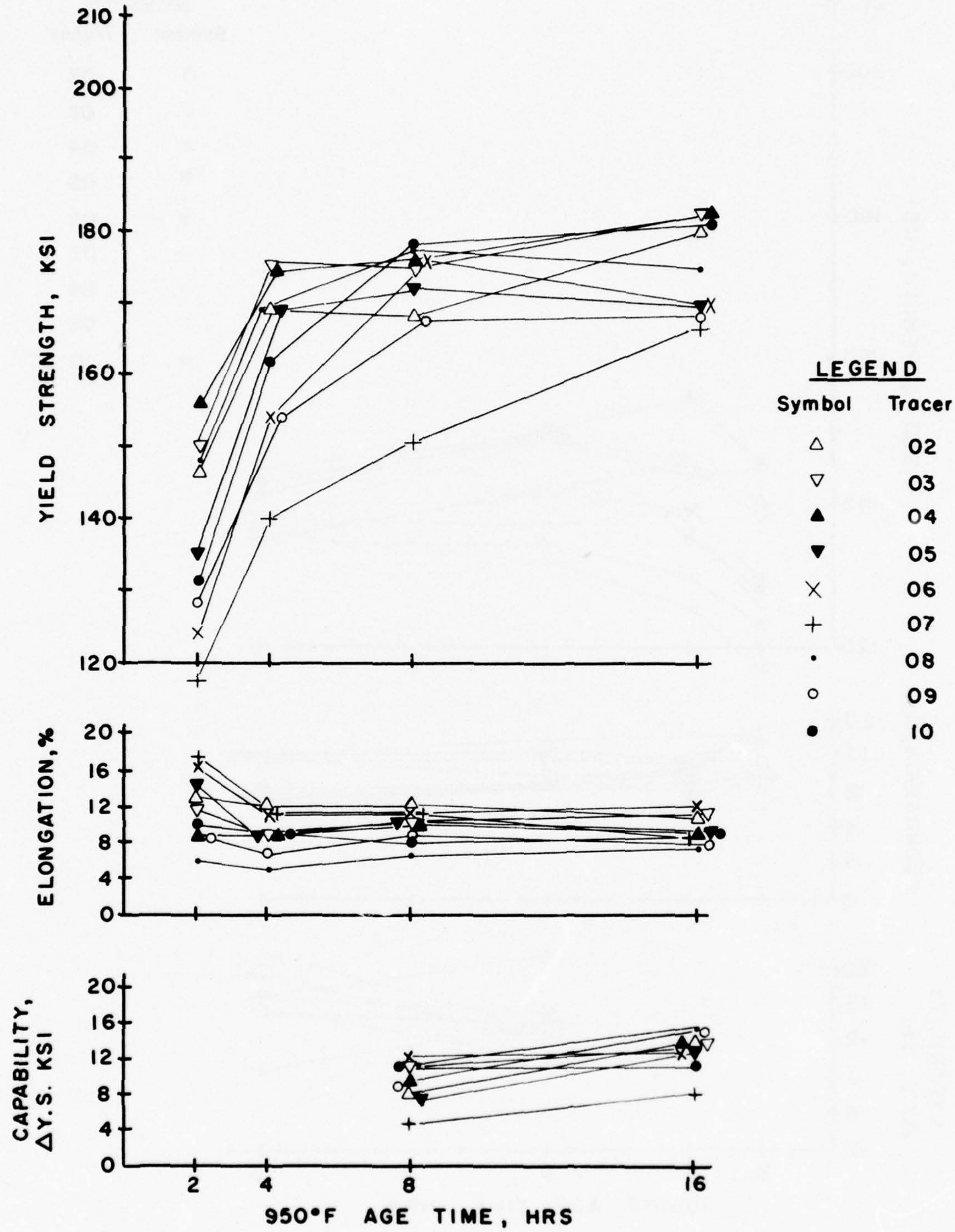


FIGURE 17. Ti-15V-3Cr-3Al-3Sn Alloy 950°F Aged Yield Strength, Elongation, and Process Capability

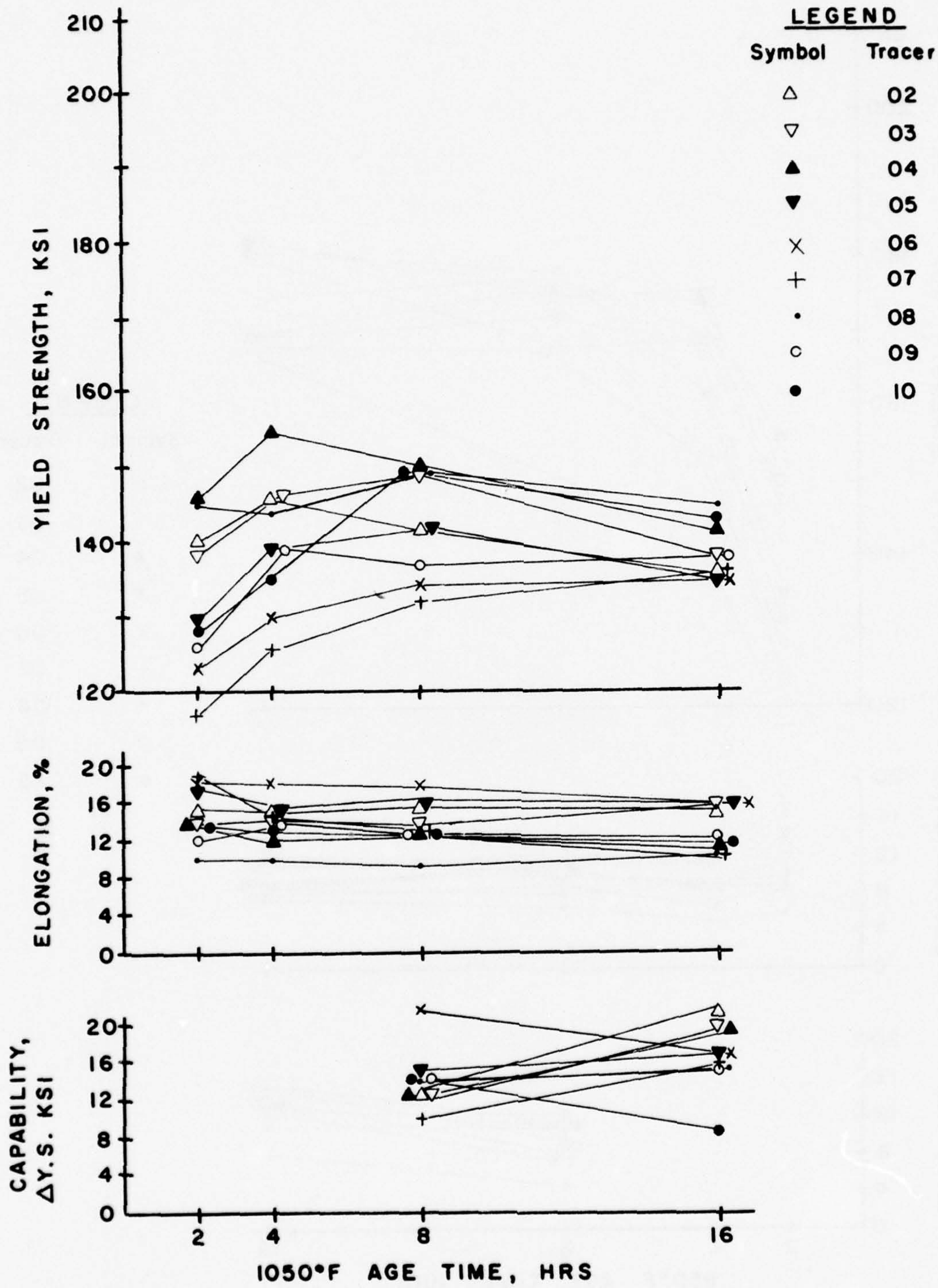


FIGURE 18. Ti-15V-3Cr-3Al-3Sn Alloy 1050°F Aged Yield Strength, Elongation, and Process Capability

Generally, the effect of processing on aged properties was significant for all three alloys. The Ti-8V-7Cr-3Al-4Sn-1Zr and Ti-8V-4Cr-2Mo-2Fe-3Al alloys aged to higher strengths than the Ti-15V-3Cr-3Al-3Sn, but adequate strength to ductility can obviously be achieved through proper selection of an aging treatment in all three alloys.

Figures 13 and 14 show 950°F and 1050°F aging characteristics for the Ti-8V-7Cr-3Al-4Sn-1Zr alloy. The yield strength and elongation are conventional tensile values. Process temperature capability is the variation in yield strength to be expected from temperature variations during the aging treatment. These values were calculated from a graph of the effect of aging temperature on yield strength for constant time, and the values shown are for the effect of a 50°F (±25°F around a set point) variation in temperature on yield strength.

In Figure 13 the yield strength response range is quite large and the results fall into three ranges based on processing. The most rapid and highest response was for the three hot rolled conditions, 08, 09, and 10. The slowest response was for the 0.050" gage strip, 02, and the 0.100" gage hot plus cold rolled condition, 06. The response for the other conditions fell in a band between the two extremes. Examination of the solution treated microstructures indicates a correlation between the three general groupings according to aging response and degree of recrystallization. The hot rolled materials (-08, -09, and -10 tracers) show essentially no recrystallization, whereas the -02 and -06 tracers for the strip and hot + cold roll processing, Figures 4, 8, and 9, show the greatest amount of recrystallization. For present purposes full recrystallization is desired.

At 1050°F, Figure 14, the aging response for the cold rolled materials fall into one range from about 147 to 164 Ksi after 16 hours aging but are still somewhat lower than for the hot rolled materials.

Further study showed that the aging response for hot rolled material from this Ti-8V-7Cr-3Al-4Sn-1Zr alloy could be brought into the strength and ductility range for the cold rolled material by additional annealing treatments.

A 1650°F-6min. anneal was shown to recrystallize the hot rolled material so tensile blanks were batch vacuum annealed with these conditions, fast cooled, and aged at 1050°F with the results shown below:

	Ti-8V-7Cr-3Al-4Sn-1Zr Alloy Yield Strength, Ksi		
1050°F Age Time, Hrs	-08 1750°F Hot Rolled 0.100"	-09 1750°F Hot Rolled 0.050"	-10 1850°F Hot Rolled 0.100"
2	130	132	137
8	163	166	169
16	166	159	165

Tensile strength and elongation values for these conditions also were close to those for the conditions involving cold reduction.

The aging results for the Ti-8V-4Cr-2Mo-2Fe-3Al alloy in Figures 15 and 16 generally fall into one range narrower than for the Ti-8V-7Cr-3Al-4Sn-1Zr alloy. The hot plus cold rolled 0.050" gage sheet (-07) has the slower aging response, and comparison of the microstructures in Figure 9 with those for the other as produced conditions shows more complete recrystallization for the -07 tracer material. The association between recrystallization and aging uniformity between the two alloys follows from a comparison of microstructures since the Ti-8V-4Cr-2Mo-2Fe-3Al alloy recrystallized more completely at 1500°F than the Ti-8V-7Cr-3Al-4Sn-1Zr annealed at the lower temperature.

The aged strength for the Ti-15V-3Cr-3Al-3Sn alloy at 950°F and 1050°F was lower than for the other two alloys. Tensile elongation values showed a correspondence with strength level comparable to the other two alloys. The effect of processing for this alloy was similar to the other two alloys.

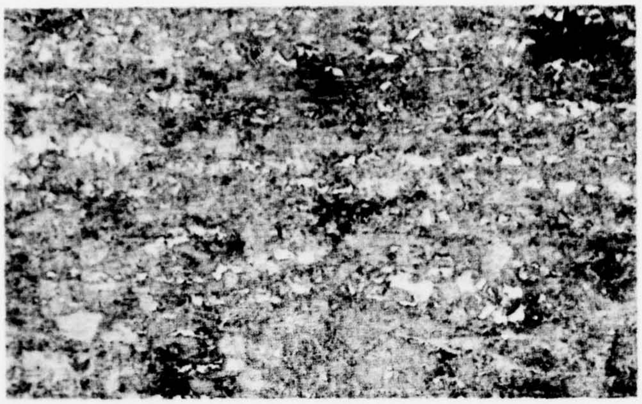
Typical aged microstructures for the Ti-8V-7Cr-3Al-4Sn-1Zr alloy are shown in Figure 19. The effect of three degrees of recrystallization are evident with light etching grain boundaries in the cold rolled material and more uniform etching in the hot rolled material except the few dark spots where recrystallized grains have formed. The differences in darkening between these photomicrographs is probably not too significant because of differences in etching characteristics. The -02 and -04 conditions etched very rapidly, whereas, the -09 hot rolled condition could not be darkened by overetching.

The aged microstructures for the Ti-8V-4Cr-2Mo-2Fe-3Al and Ti-15V-3Cr-3Al-3Sn alloys are shown in Figures 20 and 21, respectively. The structure of the hot rolled Ti-15V-3Cr-3Al-3Sn alloy contains a mixture of recrystallized and unrecrystallized material, and the difference in etching response has clearly distinguished them.

Process capabilities for all the alloys and conditions were in a range from 3 to about 22 Ksi yield strength. Generally in the selection of age treatments the strength level and the aim for the overaged condition had to be given more consideration than process capability.

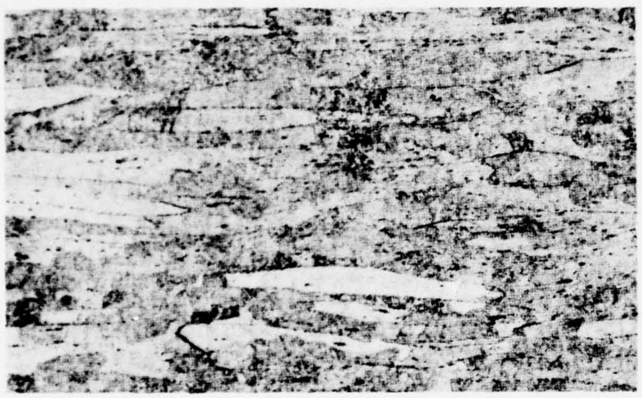
The aging conditions selected for second tier testing along with tensile properties and process capabilities are shown in Table 16. The criteria used were 1) yield strengths in the 150 to 170 range, 2) elongation values of 8 per cent or better, 3) overaging or a relatively small change in strength in the time period, and 4) the least variation in process capability if a choice existed.

The hot rolled conditions were dropped from further mechanical property evaluation because the amount of orange peel in the bend tests would have been detrimental to formability. Additional formability evaluation study was added in place of these deleted items.



V5029-02, 0.050" Gage
Lab Simulated Strip
Annealed 1400°F-5min.
+ Aged 950°F-8hrs.

75-24A 100X



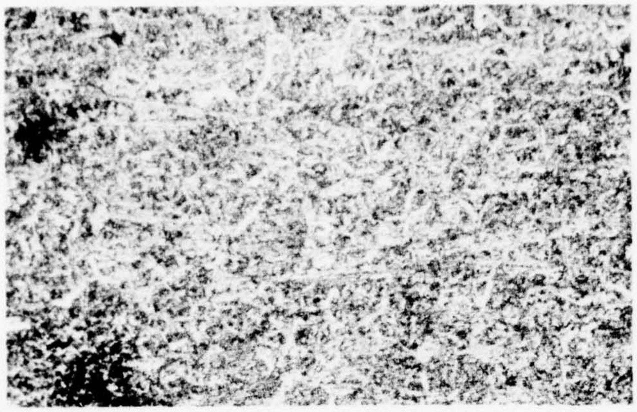
V5029-04, 0.100" Gage
Sheet Simulated Strip
Annealed 1400°F-5min.
+ Aged 950°F-8hrs.

75-24C 100X

V5029-09, 0.050" Gage
Hot Rolled Sheet
Annealed 1400°F-20min.
+ Aged 950°F-8hrs.

75-24H 100X

FIGURE 19. Aged Microstructures for Three Conditions of Ti-8V-7Cr-3Al-4Sn-1Zr.

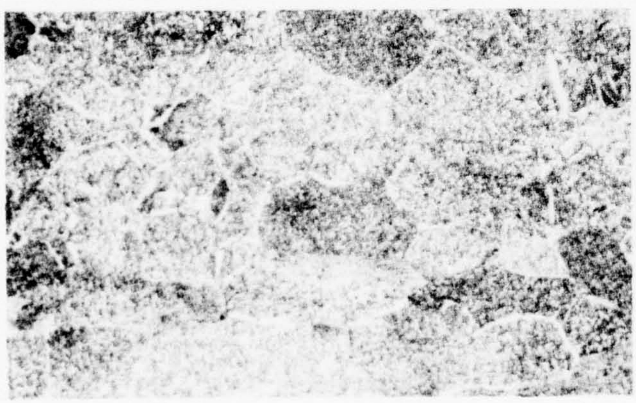


V5030-02, 0.050" Gage
Lab Simulated Strip
Annealed 1500°F-5min.
+ Aged 1050°F-8hrs.

75-19A 100X

V5030-04, 0.100" Gage
Sheet Simulated Strip
Annealed 1500°F-5min.
+ Aged 1050°F-8hrs.

75-19C 100X



V5030-09, 0.050" Gage
Hot Rolled Sheet
Annealed 1500°F-20min.
+ Aged 1050°F-16hrs.

75-19F 100X

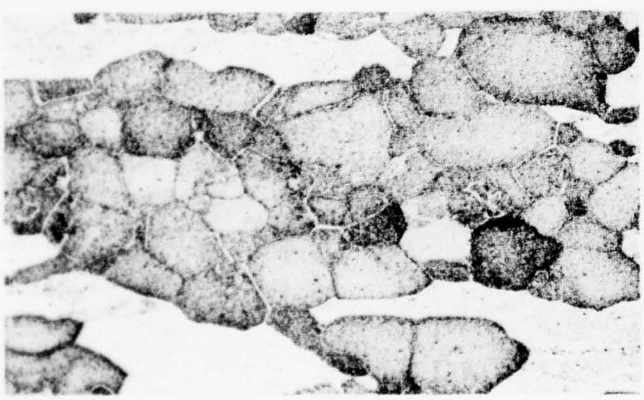
FIGURE 20. Aged Microstructures of Three Conditions of Ti-8V-4Cr-2Mo-2Fe-3Al.

V5031-02, 0.050" Gage
Lab Simulated Strip
Annealed 1450°F-5min.
+ Aged 950°F-8hrs.

75-19H 100X

V5031-04, 0.100" Gage
Sheet Simulated Strip
Annealed 1450°F-5min.
+ Aged 950°F-8hrs.

75-19J 100X



V5031-09, 0.050" Gage
Hot Rolled Sheet
Annealed 1450°F-20min.
+ Aged 950°F-8hrs.

75-19M 100X

FIGURE 21. Aged Microstructures for Three Conditions of Ti-15V-3Cr-3Al-3Sn Alloy.

TABLE 16

AGING TREATMENTS SELECTED FOR SECOND TIER TESTING

Processing	Gage, In.	Aging Treatment Temp, °F	Aging Treatment Time, Hrs	Tensile Properties UTS, Ksi	Tensile Properties YS, Ksi	Tensile Properties El, %	Process Capability, ΔKsi Y.S.
Ti-8V-7Cr-3Al-4Sn-1Zr Alloy, Heat V5029							
-02 Lab Simulated Strip	0.050[1]	1050	16	161	148	16	21
-03 " " "	0.100[1]	"	"	172	158	12	22
-04 Sheet " "	0.100	"	8	178	162	12	15
-05 " " "	0.050	"	"	178	160	14	14
-06 Hot + Cold Rolled Sheet	0.100	"	"	167	152	13	8
-07 " + " " "	0.050	"	"	173	157	14	12
Ti-8V-4Cr-2Mo-2Fe-3Al Alloy, Heat V5030							
-02 Lab Simulated Strip	0.050	1050	8	174	164	14	14
-03 " " "	0.100	"	"	175	165	13	14
-04 Sheet " "	0.100	"	"	172	160	14	14
-05 " " "	0.050	"	"	179	165	13	14
-06 Hot + Cold Rolled Sheet	0.100	"	16	178	165	9	16
-07 " + " " "	0.050	"	"	168	157	11	13

-continued-

TABLE 16 - continued

Processing	Gage, In.	Aging Treatment Temp, °F	Aging Treatment Time, Hrs	Tensile Properties UTS, Ksi	Tensile Properties YS, Ksi	Tensile Properties El, %	Process Capability, ΔKsi Y.S.
Ti-15V-3Cr-3Al-3Sn Alloy, Heat V5031							
-02 Lab Simulated Strip	0.050	1000	8	* 170	156	9	* 11
-03 " " "	0.100	"	"	* 170	162	12	* 12
-04 Sheet " "	0.100	"	"	* 180	164	11	* 12
-05 " " "	0.050	"	"	* 176	158	13	* 11
-06 Hot + Cold Rolled Sheet	0.100	"	"	* 168	156	14	* 9
-07 " + " " "	0.050	950	16	183	167	10	8

*Tensile properties are estimated. Process capabilities are average of 950° and 1050°F capabilities.

[1]Solution anneal 1500°F-6 min.

B. MECHANICAL PROPERTY EVALUATION FOR SELECTED AGING CONDITIONS

1. Pole Figures

Pole figures, (110) for the solution annealed condition are shown in Figures 22 through 39 for the three alloys, two gages, and three types of fabrication. The intensity figures shown are comparable between pole figures and even the highest intensity obtained, 240 in Figure 34 for the 0.050" gage hot plus cold rolled Ti-8V-7Cr-3Al-4Sn-1Zr alloy, does not represent a high degree of preferred orientation. The higher intensity pole figures are associated with unrecrystallized structures. For example, Figures 25, 31, 33, 34, and 38 have maximum intensities of 120 or higher and comparison with the microstructures in Figures 5, 7, and 9 show little or no recrystallization. The general trend indicated is toward a (110) plane parallel to the rolling plane of the sheet except for 0.100" gage hot plus cold rolled sheet of Ti-8V-4Cr-2Mo-2Fe-3Al and Ti-15V-3Cr-3Al-3Sn alloys where the trend is toward a (110) plane parallel to the plane of the sheet.

2. Tensile Directionality

The tensile directionality results for the annealed and annealed plus aged conditions are shown and also tabulated at the bottom of Figures 22 through 39 with pole figure results. The directionality trends were for lowest yield strength in the rolling direction and highest in the directions 30 to 60° from the rolling direction. The 0.100" gage Ti-8V-7Cr-3Al-4Sn-1Zr alloy had the highest annealed and annealed plus aged yield strengths 90° to the rolling direction. Aging increased directionality from an average 4 Ksi to 7 Ksi.

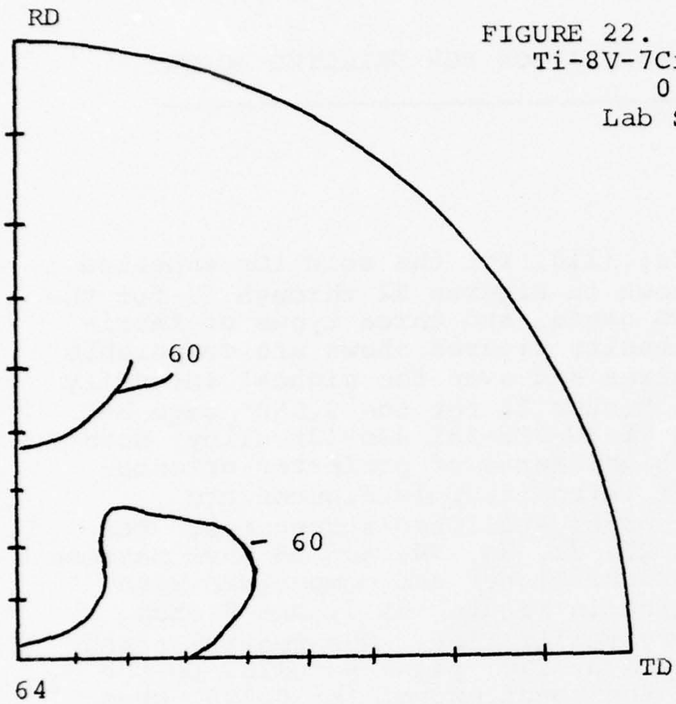


FIGURE 22. (110) Pole Figure for
Ti-8V-7Cr-3Al-4Sn-1Zr Alloy
0.050" Gage
Lab Simulated Strip

Solution Treated and Solution Treated and Aged
Tensile and Bend Properties

Test Direction	Tensile Properties TS, Ksi	YS, Ksi	El, %	E, $x10^6$	Bend Min, xT,20X
Solution Treated 1400°F-6min.AC					
RD	124	122	24	11.9	2.6
30	128	123	16	13.1	-
45	127	124	19	13.6	-
60	126	123	16	14.2	-
TD	123	122	21	11.8	4.0
Solution Treated + Aged 1050°F-16hrs.AC					
RD	159	146	20	15.1	-
30	167	152	19	15.9	-
45	163	150	15	15.4	-
60	164	150	16	16.0	-
TD	165	152	-	15.0	-

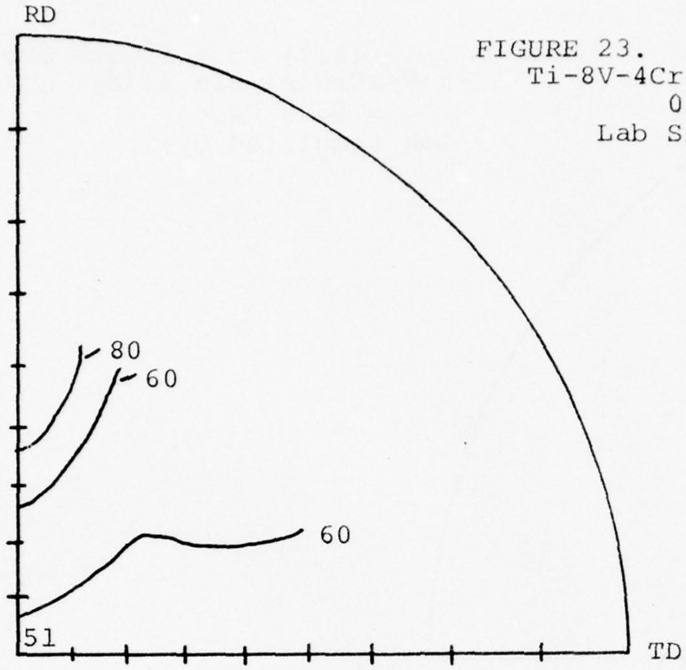


FIGURE 23. (110) Pole Figure for Ti-8V-4Cr-2Mo-2Fe-3Al Alloy 0.050" Gage Lab Simulated Strip

Solution Treated and Solution Treated and Aged Tensile and Bend Properties

Test Direction	TS, Ksi	YS, Ksi	El, %	E, x10^6	Bend Min, xT,20X
Solution Treated 1500°F-6min AC					
RD	122	120	21	11.1	2.6
30	127	125	16	13.7	-
45	128	126	16	12.9	-
60	127	125	17	12.5	-
TD	126	123	22	12.6	4.0
Solution Treated + Aged 1050°F-8hrs AC					
RD	165	155	11	15.6	-
30	176	167	12	16.8	-
45	175	161	11	16.1	-
60	173	162	14	-	-
TD	174	162	12	-	-

(Tensile Properties span TS through E; Bend spans Min, xT,20X.)

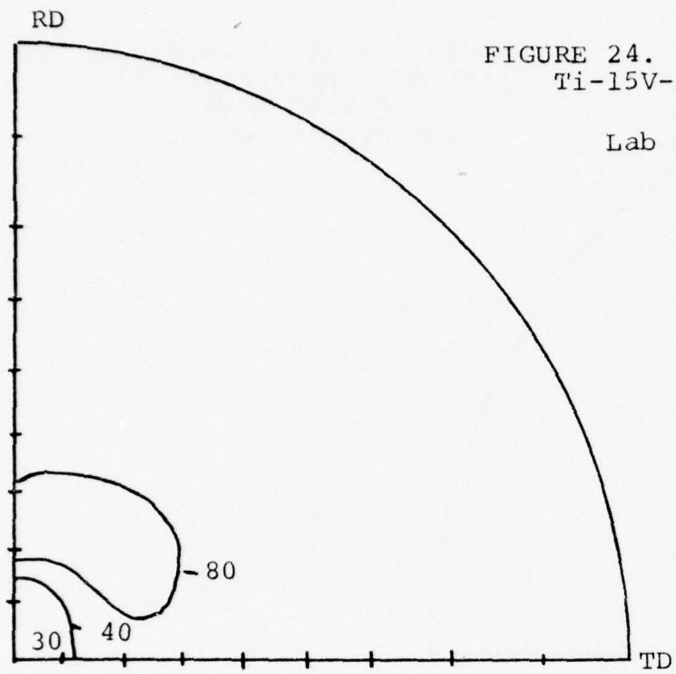


FIGURE 24. (110) Pole Figure for Ti-15V-3Cr-3Al-3Sn Alloy 0.050" Gage Lab Simulated Strip

Solution Treated and Solution Treated and Aged Tensile and Bend Properties

	Tensile Properties				Bend
Test Direction	TS, Ksi	YS, Ksi	El, %	E, $x10^6$	Min, xT,20X
Solution Treated 1450°F-6min.AC					
RD	115	112	21	10.7	2.6
30	120	116	19	11.8	-
45	119	117	15	12.8	-
60	118	115	18	12.2	-
TD	115	113	25	11.4	3.6
Solution Treated + Aged 1000°F-8hrs.AC					
RD	168	155	12	15.3	-
30	175	159	13	14.9	-
45	177	169	12	15.6	-
60	174	159	10	15.3	-
TD	171	156	13	14.5	-

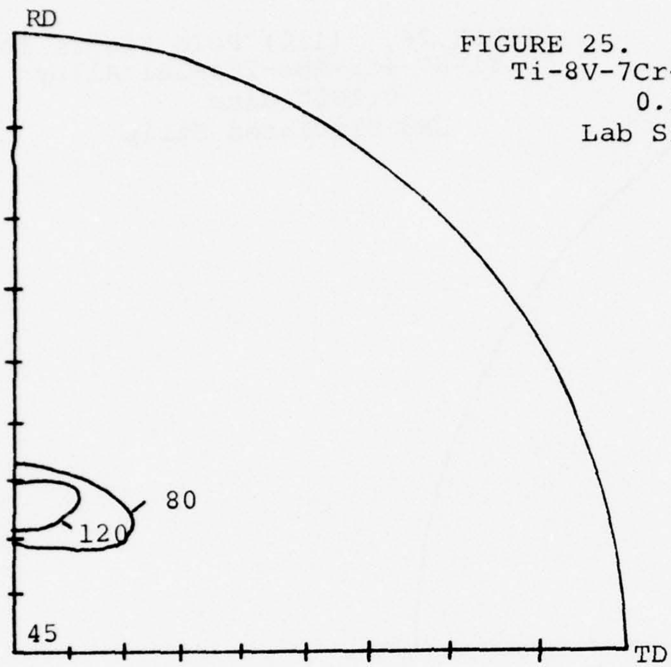


FIGURE 25. (110) Pole Figure for
Ti-8V-7Cr-3Al-4Sn-1Zr Alloy
0.100" Gage
Lab Simulated Strip

Solution Treated and Solution Treated and Aged
Tensile and Bend Properties

	Tensile Properties				Bend
Test Direction	TS, Ksi	YS, Ksi	El, %	E, $x10^6$	Min, xT,20X
Solution Treated 1400°F-6min AC					
RD	120	117	26	12.1	3.1
30	122	120	24	13.1	-
45	123	120	22	13.4	-
60	123	122	22	12.7	-
TD	126	123	22	13.6	-
Solution Treated + Aged 1050°F-16hrs AC					
RD	163	148	18	14.8	-
30	166	153	20	15.2	-
45	168	154	18	14.8	-
60	167	153	18	15.2	-
TD	173	156	15	15.5	-

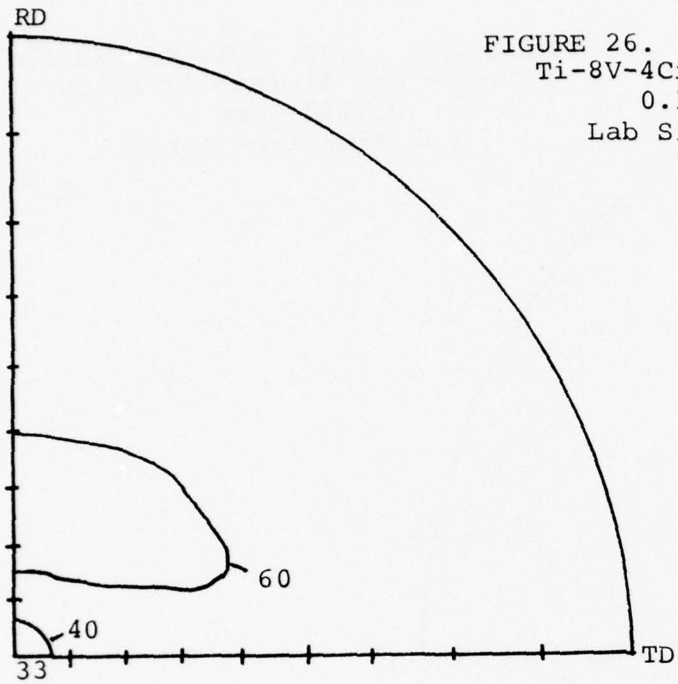


FIGURE 26. (110) Pole Figure for
Ti-8V-4Cr-2Mo-2Fe-3Al Alloy
0.100" Gage
Lab Simulated Strip

Solution Treated and Solution Treated and Aged
Tensile and Bend Properties

	Tensile Properties				Bend
Test Direction	TS, Ksi	YS, Ksi	El, %	E, $x10^6$	Min, xT,20X
Solution Treated 1500°F-6min.AC					
RD	122	118	23	11.9	3.1
30	122	119	23	11.9	-
45	123	119	22	12.4	-
60	124	120	21	12.4	-
TD	123	118	23	12.4	5.0
Solution Treated + Aged 1050°F-8hrs.AC					
RD	167	156	17	15.0	-
30	176	164	15	15.6	-
45	177	165	15	15.7	-
60	176	164	15	15.8	-
TD	170	159	18	15.4	-

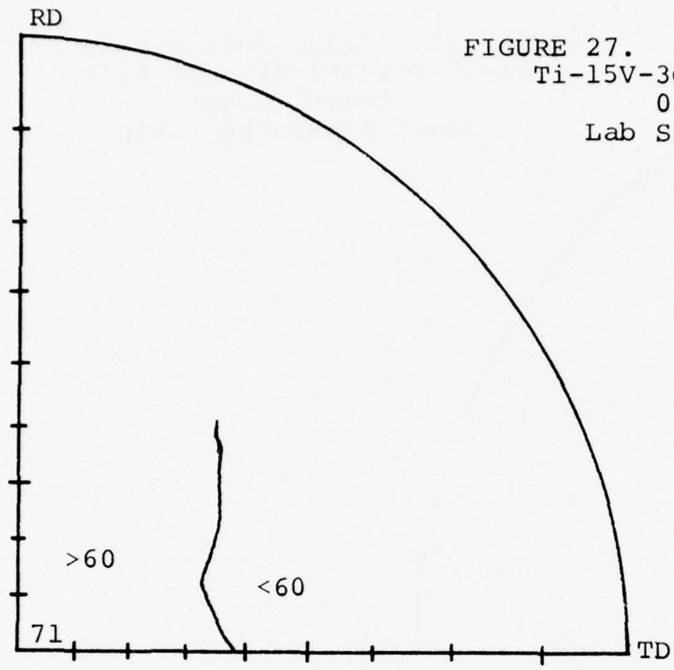


FIGURE 27. (110) Pole Figure for Ti-15V-3Cr-3Al-3Sn Alloy 0.100" Gage Lab Simulated Strip

Solution Treated and Solution Treated and Aged
Tensile and Bend Properties

	Tensile Properties				Bend
Test Direction	TS, Ksi	YS, Ksi	El, %	E, $x10^6$	Min, xT,20X
Solution Treated 1450°F-6min AC					
RD	113	110	27	11.4	3.1
30	114	111	23	11.4	-
45	115	112	23	14.2	-
60	117	114	20	12.0	-
TD	114	111	23	12.0	5.0
Solution Treated + Aged 1000°F-8hrs AC					
RD	174	156	14	14.4	-
30	173	158	15	13.9	-
45	171	152	15	14.9	-
60	174	160	12	15.1	-
TD	171	153	16	15.0	-

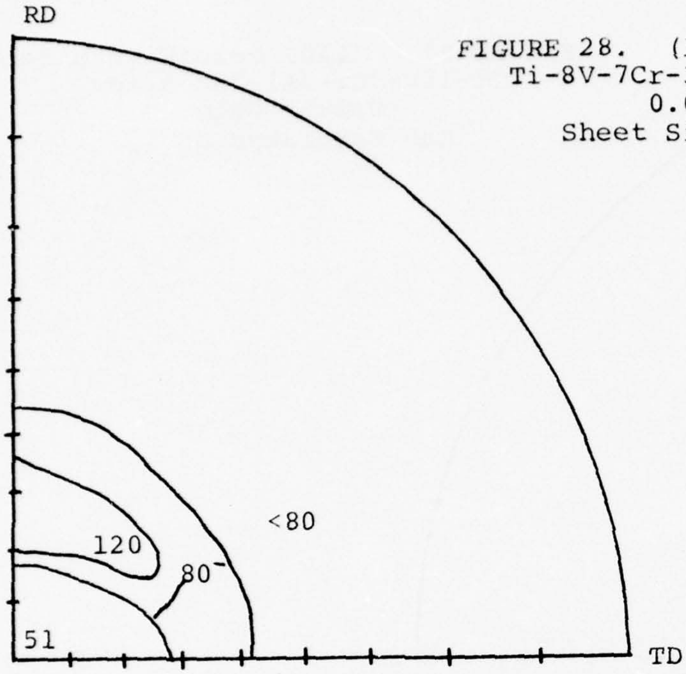


FIGURE 28. (110) Pole Figure for
Ti-8V-7Cr-3Al-4Sn-1Zr Alloy
0.050" Gage
Sheet Simulated Strip

Solution Treated and Solution Treated and Aged
Tensile and Bend Properties

Test Direction	Tensile Properties TS, Ksi	YS, Ksi	El, %	E, x10^6	Bend Min, xT, 20X
Solution Treated 1400°F-6min AC					
RD	126	123	21	12.4	2.4
30	128	126	19	12.8	-
45	129	126	21	13.3	-
60	129	126	19	13.4	-
TD	129	126	20	13.0	3.2
Solution Treated + Aged 1050°F-8hrs AC					
RD	168	153	16	14.7	-
30	174	160	15	15.2	-
45	175	160	12	15.5	-
60	173	159	14	15.0	-
TD	173	157	13	15.0	-

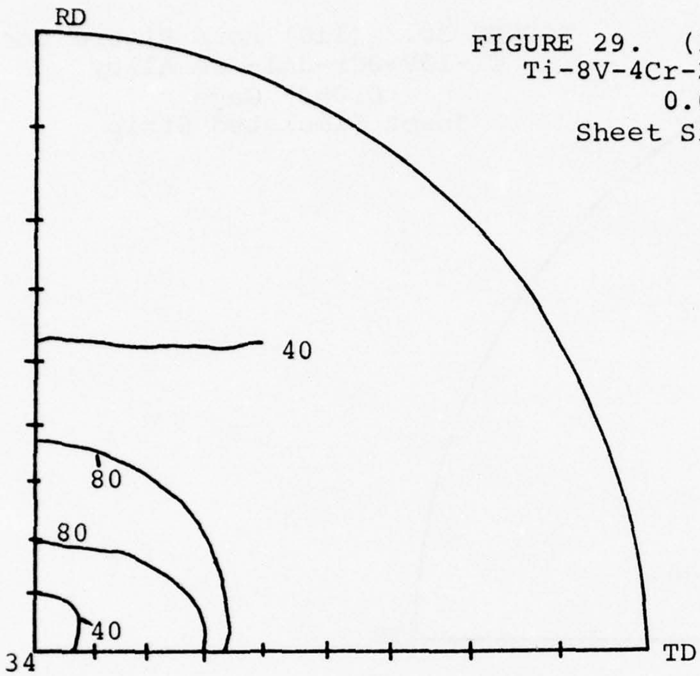


FIGURE 29. (110) Pole Figure for Ti-8V-4Cr-2Mo-2Fe-3Al Alloy 0.050" Gage Sheet Simulated Strip

Solution Treated and Solution Treated and Aged
Tensile and Bend Properties

Test Direction	TS, Ksi	YS, Ksi	El, %	E, x10^6	Bend: Min, xT,20X
Tensile Properties					Bend
Solution Treated 1500°F-6min AC					
RD	122	119	24	11.8	2.4
30	126	123	19	12.4	-
45	128	125	18	12.9	-
60	127	124	20	13.1	-
TD	124	121	25	11.6	2.5
Solution Treated + Aged 1050°F-8hrs AC					
RD	164	152	18	15.5	-
30	173	156	15	15.8	-
45	168	156	14	15.7	-
60	178	166	14	15.8	-
TD	165	152	18	15.4	-

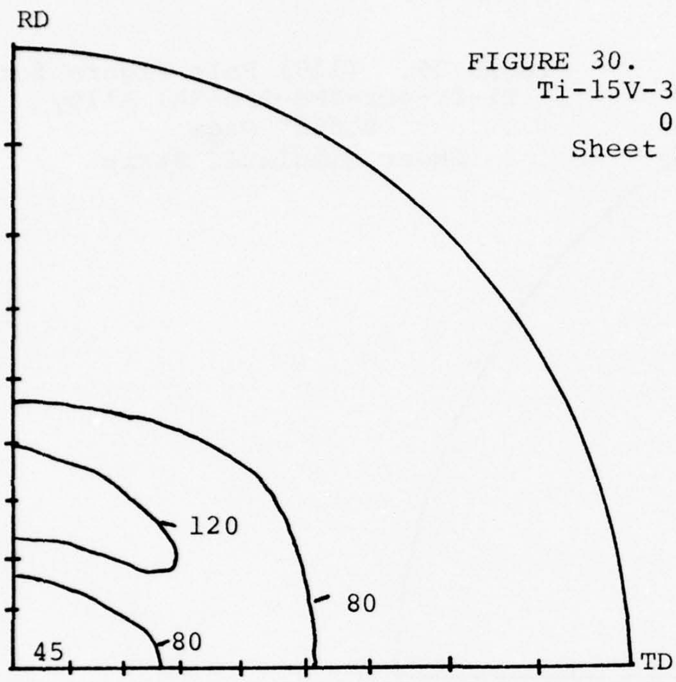


FIGURE 30. (110) Pole Figure for
Ti-15V-3Cr-3Al-3Sn Alloy
0.050" Gage
Sheet Simulated Strip

Solution Treated and Solution Treated and Aged
Tensile and Bend Properties

	Tensile Properties				Bend
Test Direction	TS, Ksi	YS, Ksi	El, %	E, x10^6	Min, xT,20X
Solution Treated 1450°F-6min AC					
RD	112	109	26	11.2	2.4
30	116	114	25	11.8	-
45	118	115	18	12.7	-
60	118	114	21	12.5	-
TD	114	112	23	11.6	2.5
Solution Treated + Aged 1000°F-8hrs AC					
RD	165	150	15	13.7	-
30	172	155	15	15.3	-
45	173	155	12	15.3	-
60	171	155	13	14.8	-
TD	168	151	14	14.8	-

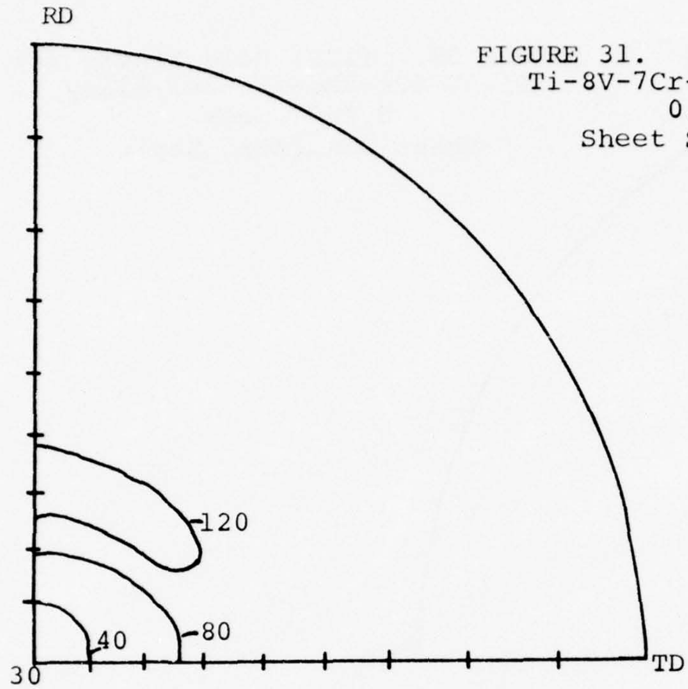


FIGURE 31. (110) Pole Figure for Ti-8V-7Cr-3Al-4Sn-1Zr Alloy 0.100" Gage Sheet Simulated Strip

Solution Treated and Solution Treated and Aged Tensile and Bend Properties

Test Direction	Tensile Properties TS, Ksi	YS, Ksi	El, %	E, $x10^6$	Bend Min, xT,20X
Solution Treated 1400°F-6min AC					
RD	122	118	27	11.4	3.1
30	127	123	24	13.6	-
45	126	122	20	13.2	-
60	125	122	18	13.1	-
TD	124	121	26	12.9	2.0
Solution Treated + Aged 1050°F-8hrs AC					
RD	162	150	18	14.3	-
30	167	153	17	14.9	-
45	168	154	17	15.2	-
60	164	152	16	15.3	-
TD	162	149	19	14.6	-

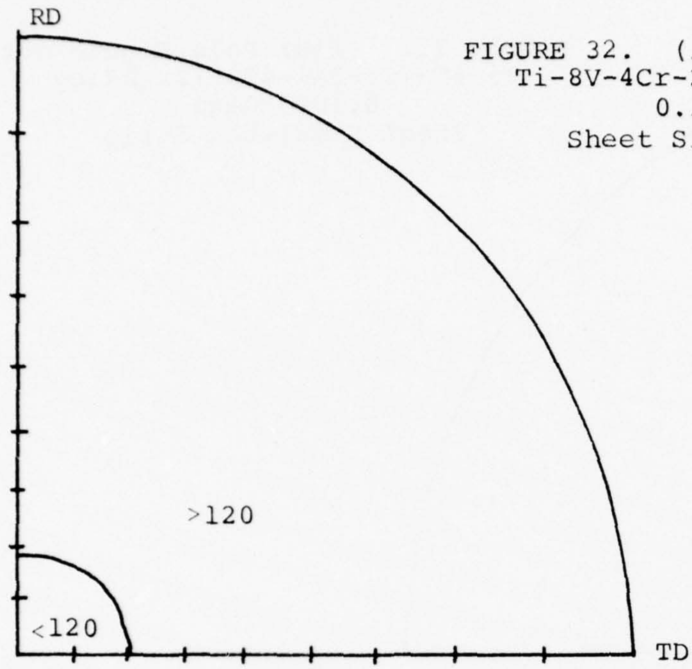


FIGURE 32. (110) Pole Figure for Ti-8V-4Cr-2Mo-2Fe-3Al Alloy 0.100" Gage Sheet Simulated Strip

Solution Treated and Solution Treated and Aged Tensile and Bend Properties

	Tensile Properties				Bend
Test Direction	TS, Ksi	YS, Ksi	El, %	E, x10^6	Min, xT,20X
Solution Treated 1500°F-6min AC					
RD	119	117	25	11.7	3.1
30	124	119	23	12.9	-
45	125	122	20	13.1	-
60	127	127	19	14.7	-
TD	120	117	25	11.8	2.1
Solution Treated + Aged 1050°F-8hrs AC					
RD	169	160	15	15.0	-
30	174	167	15	15.1	-
45	176	165	14	15.8	-
60	177	166	14	15.9	-
TD	173	163	16	15.4	-

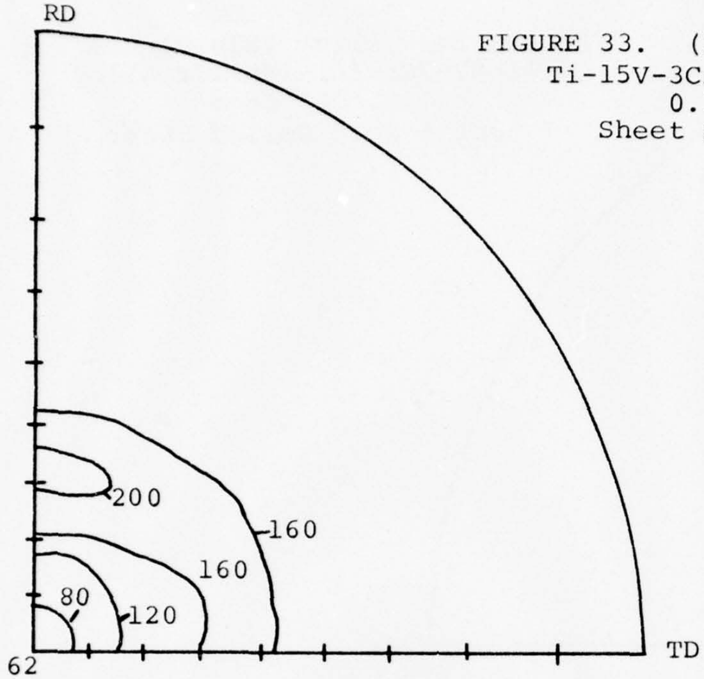


FIGURE 33. (110) Pole Figure for Ti-15V-3Cr-3Al-3Sn Alloy 0.100" Gage Sheet Simulated Strip

Solution Treated and Solution Treated and Aged Tensile and Bend Properties

Test Direction	TS, Ksi	YS, Ksi	El, %	E, $x10^6$	Bend Min, xT,20X
Solution Treated 1450°F-6min AC					
RD	110	106	27	11.7	3.1
30	111	109	25	12.5	-
45	111	108	25	12.5	-
60	112	110	25	12.3	-
TD	112	109	25	12.4	2.1
Solution Treated + Aged 1000°F-8hrs AC					
RD	172	155	14	14.5	-
30	173	157	14	14.8	-
45	173	158	13	14.6	-
60	173	158	14	14.8	-
TD	175	158	13	15.1	-

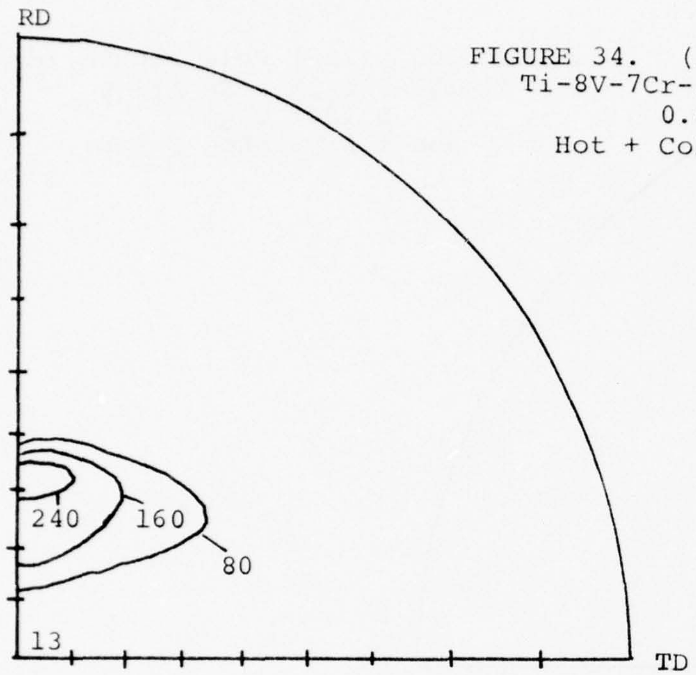


FIGURE 34. (110) Pole Figure for
Ti-8V-7Cr-3Al-4Sn-1Zr Alloy
0.050" Gage
Hot + Cold Rolled Sheet

Solution Treated and Solution Treated and Aged
Tensile and Bend Properties

Test Direction	TS, Ksi	YS, Ksi	El, %	E, x10^6	Bend Min, xT, 20X
Solution Treated 1400°F-20min AC					
RD	126	124	25	12.2	2.6
30	129	126	19	12.8	-
45	130	128	20	13.2	-
60	131	128	20	13.1	-
TD	129	127	20	13.1	2.0
Solution Treated + Aged 1050°F-8hrs AC					
RD	168	151	16	14.8	-
30	171	155	14	16.2	-
45	176	161	17	16.1	-
60	175	160	16	15.9	-
TD	173	158	16	15.8	-

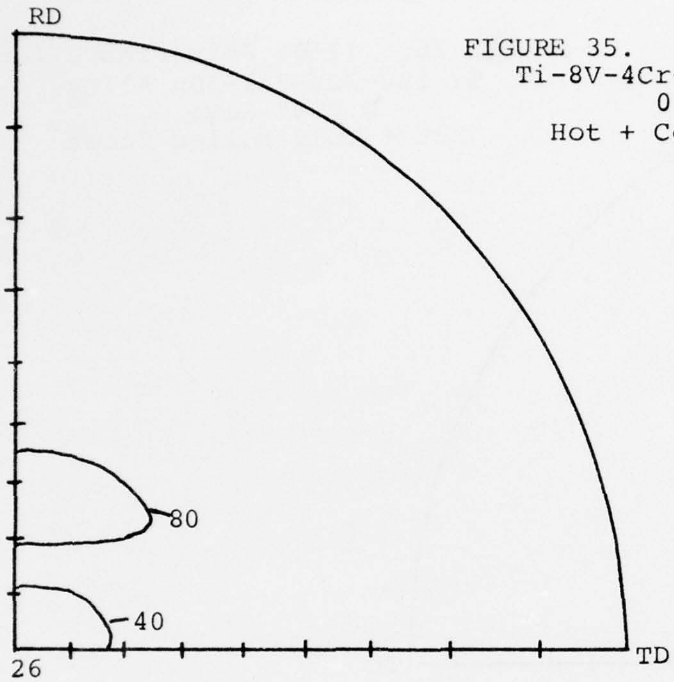


FIGURE 35. (110) Pole Figure for Ti-8V-4Cr-2Mo-2Fe-3Al Alloy 0.050" Gage Hot + Cold Rolled Sheet

Solution Treated and Solution Treated and Aged
Tensile and Bend Properties

	Tensile Properties				Bend
Test Direction	TS, Ksi	YS, Ksi	El, %	E, $x10^6$	Min, xT,20X
Solution Treated 1500°F-20min AC					
RD	125	119	26	12.2	2.6
30	125	122	24	12.9	-
45	126	122	16	12.7	-
60	125	122	23	13.7	-
TD	123	120	25	12.7	2.1
Solution Treated + Aged 1050°F-16hrs AC					
RD	175	165	15	15.4	-
30	179	169	14	15.9	-
45	180	170	15	16.2	-
60	182	170	10	16.3	-
TD	177	168	14	15.8	-

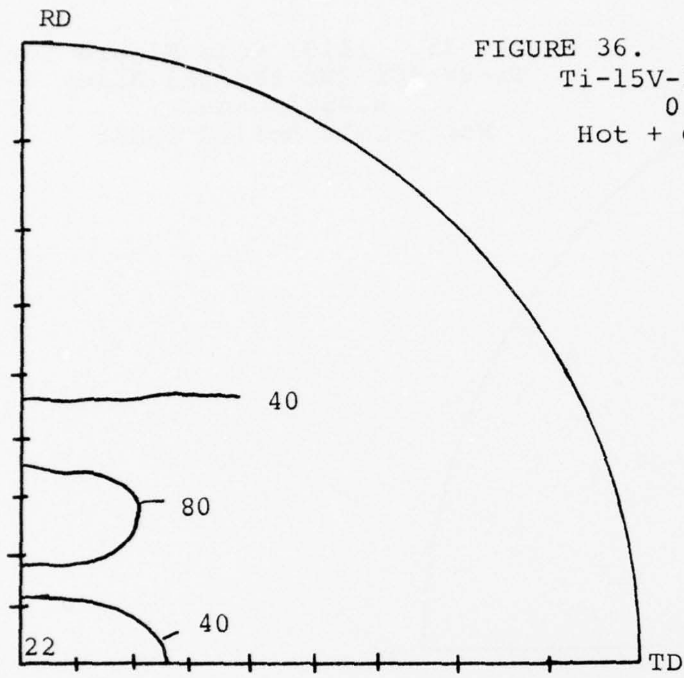


FIGURE 36. (110) Pole Figure for
Ti-15V-3Cr-3Al-3Sn Alloy
0.050" Gage
Hot + Cold Rolled Sheet

Solution Treated and Solution Treated and Aged
Tensile and Bend Properties

	Tensile Properties				Bend
Test Direction	TS, Ksi	YS, Ksi	El, %	E, x10^6	Min, xT,20X
Solution Treated 1450°F-20min AC					
RD	111	108	25	11.5	2.6
30	113	110	24	12.7	-
45	114	112	22	12.4	-
60	114	111	21	12.3	-
TD	114	110	24	12.0	2.1
Solution Treated + Aged 950°F-16hrs AC					
RD	179	165	13	15.6	-
30	181	166	13	15.2	-
45	182	167	13	16.0	-
60	182	169	10	15.2	-
TD	179	167	13	15.7	-

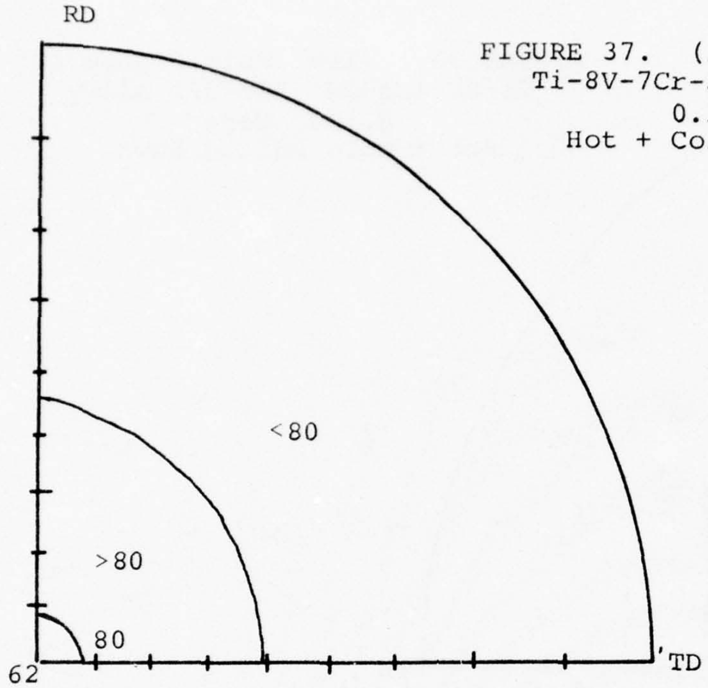


FIGURE 37. (110) Pole Figure for Ti-8V-7Cr-3Al-4Sn-1Zr Alloy
0.100" Gage
Hot + Cold Rolled Sheet

Solution Treated and Solution Treated and Aged
Tensile and Bend Properties

	Tensile Properties				Bend
Test Direction	TS, Ksi	YS, Ksi	El, %	E, x10^6	Min, xT, 20X
Solution Treated 1400°F-20min AC					
RD	120	116	25	12.3	3.1
30	121	117	22	13.2	-
45	123	118	22	13.6	-
60	122	118	22	13.5	-
TD	123	117	23	13.1	2.5
Solution Treated + Aged 1050°F-8hrs AC					
RD	161	145	19	14.6	-
30	168	156	15	15.3	-
45	167	152	15	15.4	-
60	158	145	15	14.6	-
TD	160	146	16	15.5	-

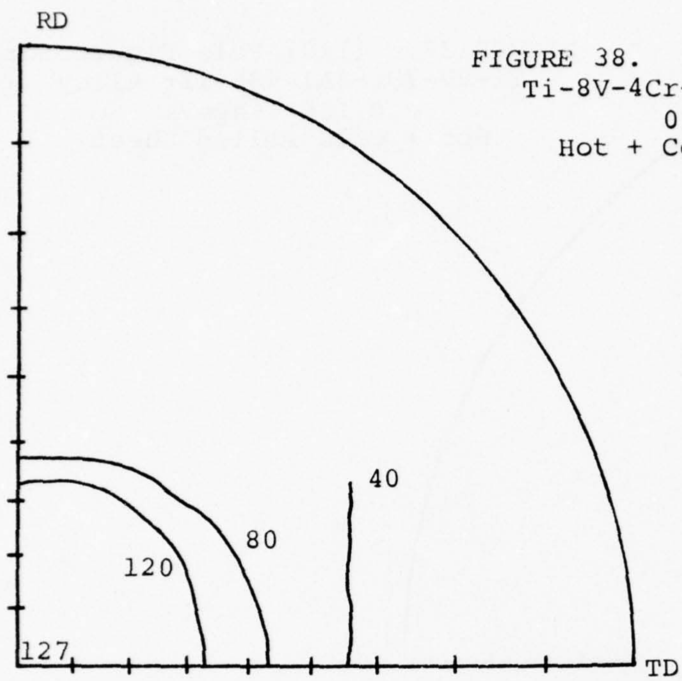


FIGURE 38. (110) Pole Figure for
Ti-8V-4Cr-2Mo-2Fe-3Al Alloy
0.100" Gage
Hot + Cold Rolled Sheet

Solution Treated and Solution Treated and Aged
Tensile and Bend Properties

Test Direction	TS, Ksi	YS, Ksi	El, %	E, $x10^6$	Bend: Min, xT,20X
	Tensile Properties				
Solution Treated 1500°F-20min AC					
RD	120	116	24	12.4	3.1
30	121	117	22	13.1	-
45	122	117	23	12.9	-
60	122	119	22	12.9	-
TD	123	120	23	13.0	-
Solution Treated + Aged 1050°F-16hrs AC					
RD	170	153	16	15.3	-
30	172	158	13	15.5	-
45	171	161	15	15.7	-
60	172	164	15	16.1	-
TD	174	163	12	15.8	-

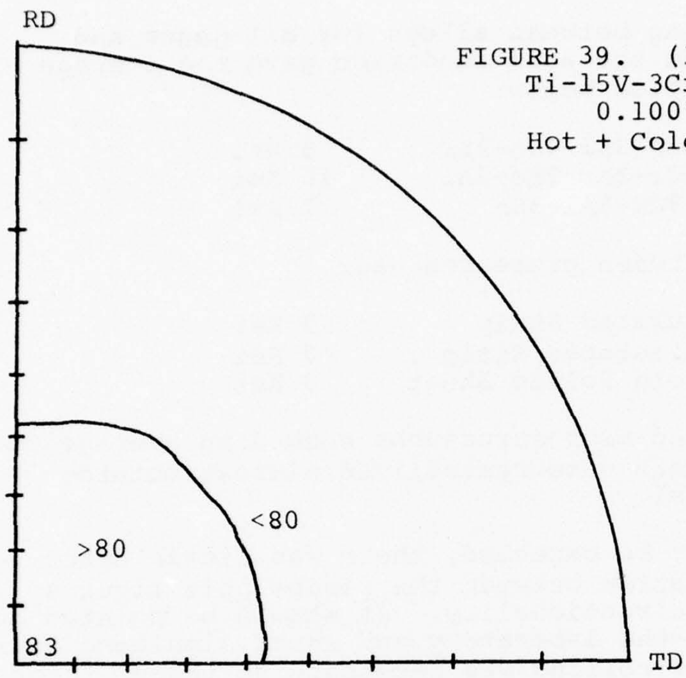


FIGURE 39. (110) Pole Figure for Ti-15V-3Cr-3Al-3Sn Alloy 0.100" Gage Hot + Cold Rolled Sheet

Solution Treated and Solution Treated and Aged Tensile and Bend Properties

Test Direction	TS, Ksi	YS, Ksi	El, %	E, x10^6	Bend Min, xT, 20X
Solution Treated 1450°F-20min AC					
RD	108	106	26	11.6	3.1
30	111	108	23	12.2	-
45	112	110	22	12.6	-
60	111	108	24	12.6	-
TD	110	107	25	11.9	2.5
Solution Treated + Aged 1000°F-8hrs AC					
RD	167	153	14	14.2	-
30	171	155	14	15.2	-
45	173	160	15	15.7	-
60	173	158	15	15.4	-
TD	172	157	15	15.2	-

Comparing between alloys for all gages and conditions in the aged condition gave the average directionalities below:

Ti-8V-7Cr-3Al-4Sn-1Zr	8 Ksi
Ti-8V-4Cr-2Mo-2Fe-3Al	10 Ksi
Ti-15V-3Cr-3Al-3Sn	7 Ksi

Comparing between processes had:

Lab Simulated Strip	9 Ksi
Sheet Simulated Strip	7 Ksi
Hot + Cold Rolled Sheet	8 Ksi

Recrystallized microstructures showed an average of 7.9 Ksi whereas unrecrystallized microstructures averaged 7 Ksi.

As might be expected, there was little detectable correlation between the random pole figures and tensile directionality. It should be pointed out that in both the laboratory and sheet simulated strip process cross rolling was necessary at the 3" thick sheet bar stage which would not be possible in commercially produced strip. Unidirectional rolling might increase directionality, however, low directionality has been found in unidirectionally rolled Ti-8Mo-8V-2Fe-3Al alloy strip as shown below:

		Aged Tensile Properties for 1000F-6hrs AC (6)			
Gage, In.	Test Direction	TS, Ksi	YS, Ksi	Elong, %	E x10
0.060	L	177	158	15.5	14.8
"	T	178	161	13.3	16.1
0.040	L	178	160	14.5	15.0
"	T	181	162	12.8	15.3
0.020	L	186	171	12.8	15.9
"	T	189	175	11	16.2

No published data on directionality are available for unidirectionally rolled strip of the beta type alloys of the other producers.

(6) "Beta Titanium Alloys", MCIC-72-11, Report dated September 1972, by Mr. R. A. Wood.

3. Fracture Toughness and Notched Fatigue

Fracture toughness results and a summary of notched fatigue results for a K_t-3.5, R-0.1 are shown in Table 17. Averaging results for the alloys over gages and processes, there is little basis in the fracture toughness results for selection of one alloy over the other. The aged K_Q values of 81 to 118 Ksi$\sqrt{in}$ are high considering the 145 to 165 Ksi yield strength range for the materials.

The notched fatigue results for lab simulated strip Ti-15V-3Cr-3Al-3Sn alloy are lower than the other two alloys. The other two processing conditions show similar results for all three alloys, but without tension in rolling the average results are higher for all three alloys. Obviously with only five test samples used these results are indicative of trends only.

4. Precision Modulus and Compressive Strength

Precision modulus and compressive strength are shown in Table 18. The aged Tuckerman tensile modulus values show an advantage for the Ti-8V-4Cr-2Mo-2Fe-3Al alloy with an average value of about 15.8 as compared to 15.2 and 15.1 for the Ti-8V-7Cr-3Al-4Sn-1Zr and Ti-15V-3Cr-3Al-3Sn alloys, respectively. A similar relationship was not observed from the compression modulus values either because it does not exist or because the precision in this determination is lacking.

5. Crack Growth

Crack growth results are shown in Figures 40 through 57 where longitudinal, transverse, and salt da/dn vs. ΔK results for each aged alloy and fabrication condition are graphed in one figure. Values for A and n for the relation $da/dn = A(\Delta K)^n$ are shown in Table 19. Values of da/dn for selected ΔK levels are given in Table 20.

TABLE 17

FRACTURE TOUGHNESS AND NOTCHED FATIGUE RESULTS

Alloy	Gage, In.	Test Direction	Fracture Toughness K_Q, Ksi$\sqrt{in}$ Annealed	Aged	Stress for Notched Fatigue Runout at 10^6 cycles, Ksi [1]
Lab Simulated Strip					
Ti-8V-7Cr-3Al-4Sn-1Zr	.050	L	167	117	20
"	"	T	175	113	20
"	.100	L	173	95	27.5
"	"	T	175	96	25
Ti-8V-4Cr-2Mo-2Fe-3Al	.050	L	165	118	25
"	"	T	168	112	25
"	.100	L	164	105	20
"	"	T	166	98	20
Ti-15V-3Cr-3Al-3Sn	.050	L	157	107	20
"	"	T	157	99	15
"	.100	L	152	88	15
"	"	T	158	86	20
Sheet Simulated Strip					
Ti-8V-7Cr-3Al-4Sn-1Zr	.050	L	163	94	25
"	"	T	162	86	25
"	.100	L	161	80	25
"	"	T	157	68	20
Ti-8V-4Cr-2Mo-2Fe-3Al	.050	L	176	111	30
"	"	T	175	113	25
"	.100	L	167	91	25
"	"	T	175	95	25

-continued-

TABLE 17 - continued

Alloy	Gage, In.	Test Direction	Fracture Toughness K_Q, Ksi$\sqrt{in}$ Annealed	Aged	Stress for Notched Fatigue Runout at 10^6 cycles, Ksi [1]
Sheet Simulated Strip					
Ti-15V-3Cr-3Al-3Sn	.050	L	159	105	30
"	"	T	159	102	30
"	.100	L	170	73	25
"	"	T	169	81	25
Hot + Cold Rolled Sheet					
Ti-8V-7Cr-3Al-4Sn-1Zr	.050	L	154	94	22.5
"	"	T	158	95	25
"	.100	L	177	97	30
"	"	T	176	112	30
Ti-8V-4Cr-2Mo-2Fe-3Al	.050	L	173	94	27.5
"	"	T	176	97	25
"	.100	L	169	91	25
"	"	T	165	78	20
Ti-15V-3Cr-3Al-3Sn	.050	L	163	99	20
"	"	T	163	97	25
"	.100	L	166	109	30
"	"	T	166	107	22.5

[1] Tests on aged material at $R = 0.1$, $K_t = 3.5$

TABLE 18

PRECISION TUCKERMAN TENSILE MODULUS AND COMPRESSIVE YIELD STRENGTH RESULTS

Alloy	Gage, In.	Test Direction	Tuckerman Tensile Modulus x 10^6 Annealed	Tuckerman Tensile Modulus x 10^6 Aged	Aged Compressive YS, Ksi	Aged Compressive E $x10^6$
Lab Simulated Strip						
Ti-8V-7Cr-3Al-4Sn-1Zr	.050	L	11.77	14.82	162	13.6
"	"	T	12.04	15.05	167	14.5
"	.100	L	12.51	15.13	165	14.6
"	"	T	12.78	15.52	166	13.8
Ti-8V-4Cr-2Mo-2Fe-3Al	.050	L	11.68	15.77	168	14.5
"	"	T	12.14	15.64	168	13.8
"	.100	L	12.12	16.33	169	16.1
"	"	T	12.71	16.26	177	16.3
Ti-15V-3Cr-3Al-3Sn	.050	L	10.70	14.43	167	12.9
"	"	T	11.11	14.65	165	12.6
"	.100	L	11.85	14.81	170	14.0
"	"	T	12.10	15.78	166	14.2
Sheet Simulated Strip						
Ti-8V-7Cr-3Al-4Sn-1Zr	.050	L	12.37	15.07	168	13.2
"	"	T	13.37	15.51	170	15.0
"	.100	L	12.03	15.01	173	13.2
"	"	T	12.93	15.32	173	14.3

-continued-

TABLE 18 - continued

Alloy	Gage, In.	Test Direction	Tuckerman Tensile Modulus x 10^6 Annealed	Tuckerman Tensile Modulus x 10^6 Aged	Aged Compressive YS, Ksi	Aged Compressive E $x10^6$
Sheet Simulated Strip						
Ti-8V-4Cr-2Mo-2Fe-3Al	.050	L	11.78	15.58	164	13.8
"	"	T	12.20	15.75	164	14.0
"	.100	L	11.73	15.16	176	14.4
"	"	T	12.36	15.63	172	15.5
Ti-15V-3Cr-3Al-3Sn	.050	L	10.98	14.65	162	13.0
"	"	T	11.57	15.21	165	13.3
"	.100	L	11.85	14.95	162	13.5
"	"	T	12.81	15.58	176	13.5
Hot + Cold Rolled Sheet						
Ti-8V-7Cr-3Al-4Sn-1Zr	.050	L	11.94	14.96	160	13.4
"	"	T	13.18	15.37	167	13.7
"	.100	L	12.40	15.06	159	13.2
"	"	T	13.26	15.52	161	15.0
Ti-8V-4Cr-2Mo-2Fe-3Al	.050	L	11.89	15.57	170	13.9
"	"	T	12.38	15.85	174	14.1
"	.100	L	12.46	15.81	166	13.3
"	"	T	13.12	16.38	174	13.8
Ti-15V-3Cr-3Al-3Sn	.050	L	11.32	15.96	169	13.8
"	"	T	11.97	15.15	177	13.9
"	.100	L	11.38	14.94	163	15.0
"	"	T	11.92	14.93	164	13.2

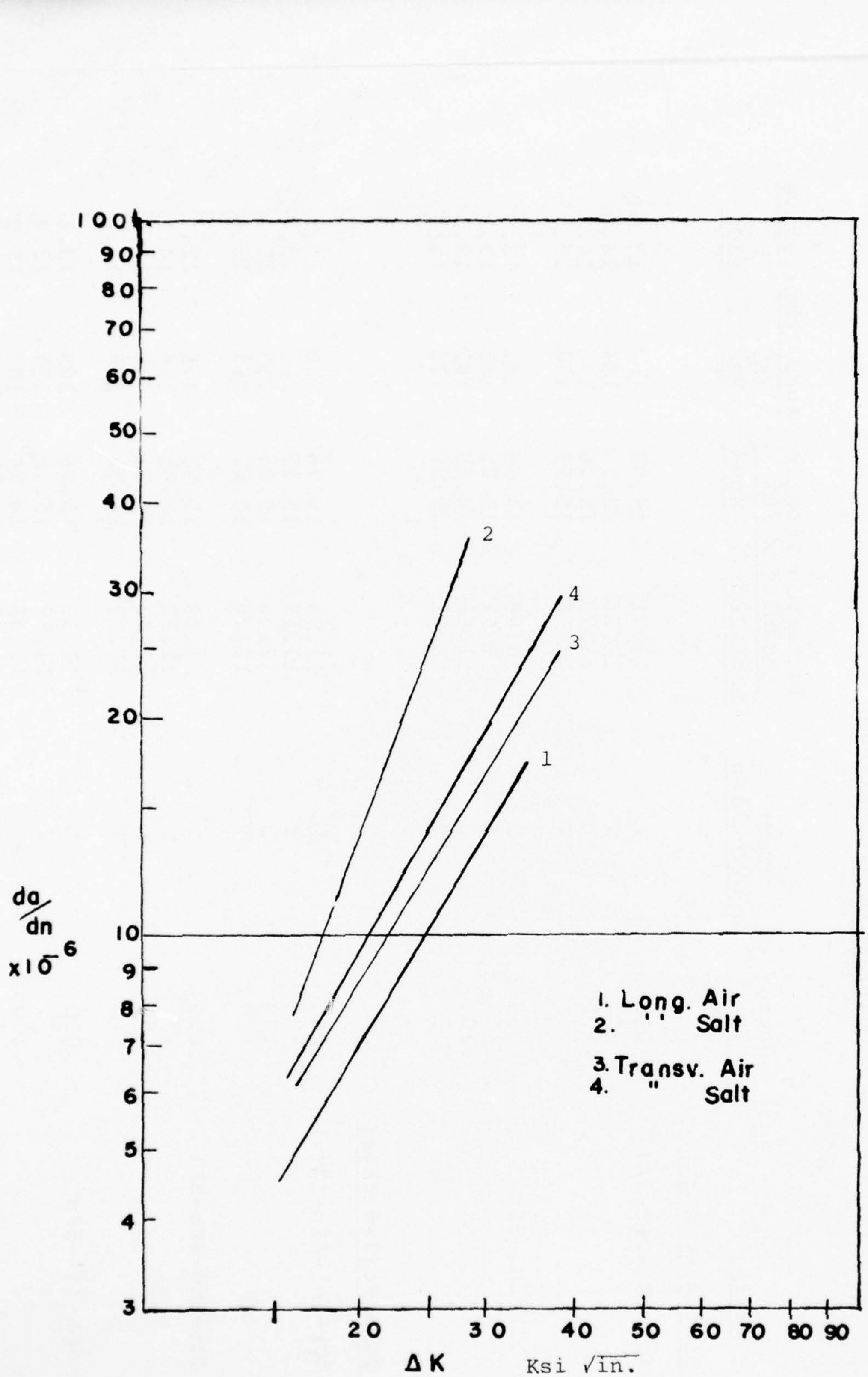


FIGURE 40. Crack Growth for 0.050" Gage
Lab Rolled Strip Ti-8V-7Cr-3Al-4Sn-1Zr Alloy

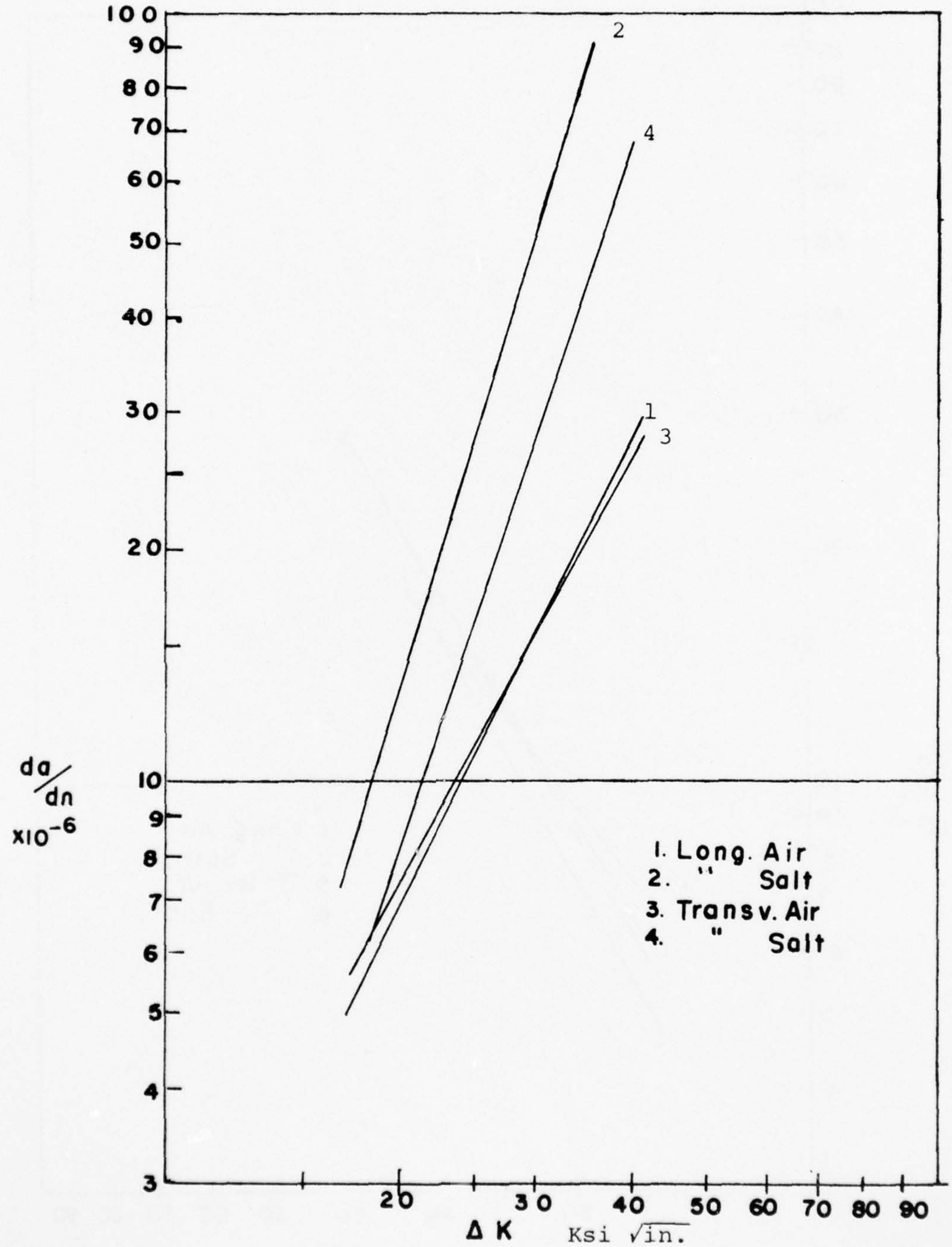


FIGURE 41. Crack Growth for 0.050" Gage Lab Rolled Strip Ti-8V-4Cr-2Mo-2Fe-3Al Alloy

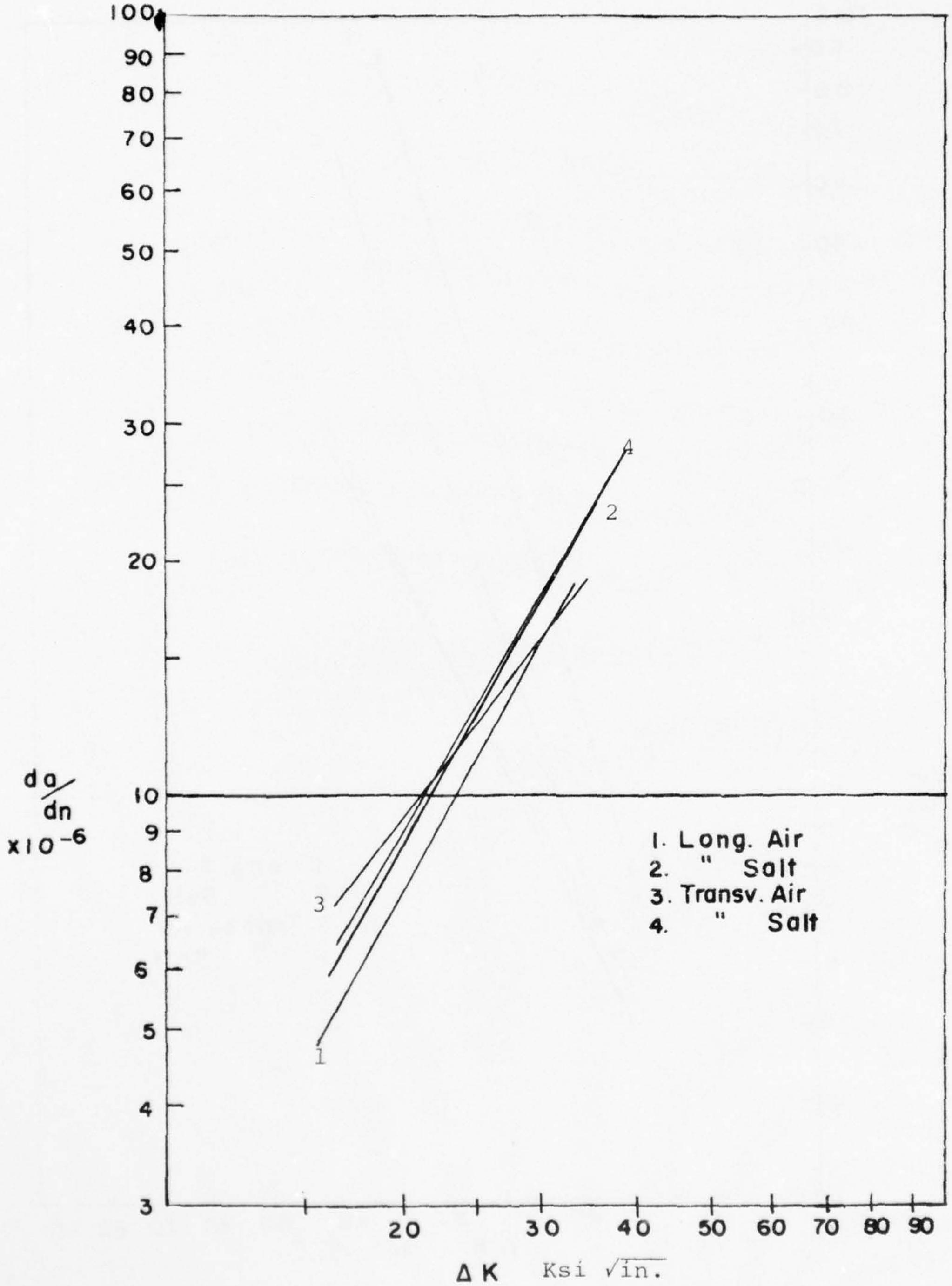


FIGURE 42. Crack Growth for 0.050" Gage
Lab Rolled Strip Ti-15V-3Cr-3Al-3Sn Alloy

AD-A033 187 TITANIUM METALS CORP OF AMERICA TORONTO OHIO TIMET DIV F/G 11/6
FORMABLE SHEET TITANIUM ALLOYS. (U)
AUG 76 G LENNING F33615-74-C-5063
UNCLASSIFIED AFML-TR-76-45 NL

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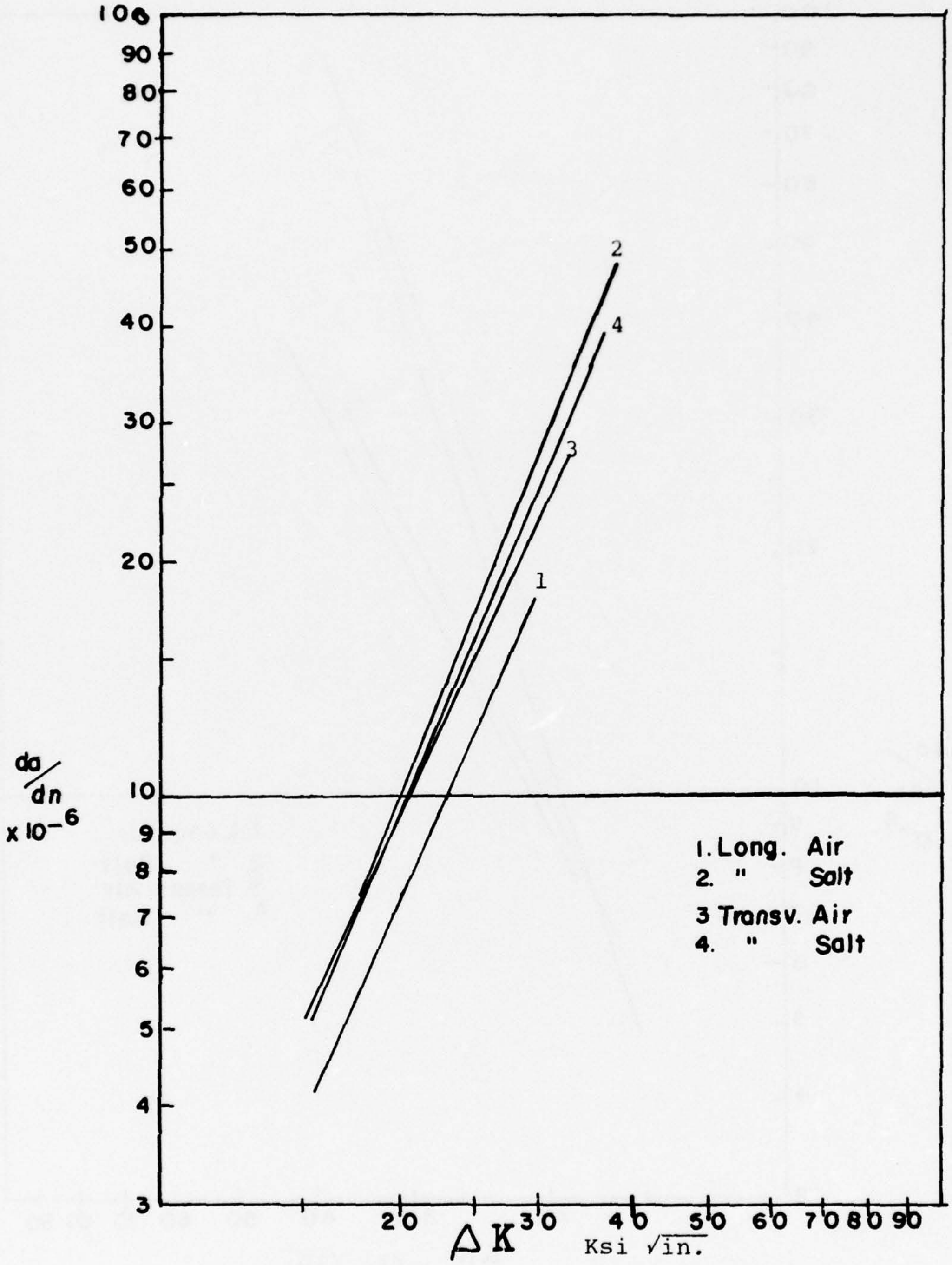

FIGURE 43. Crack Growth for 0.100" Gage
Lab Rolled Strip Ti-8V-7Cr-3Al-4Sn-1Zr Alloy

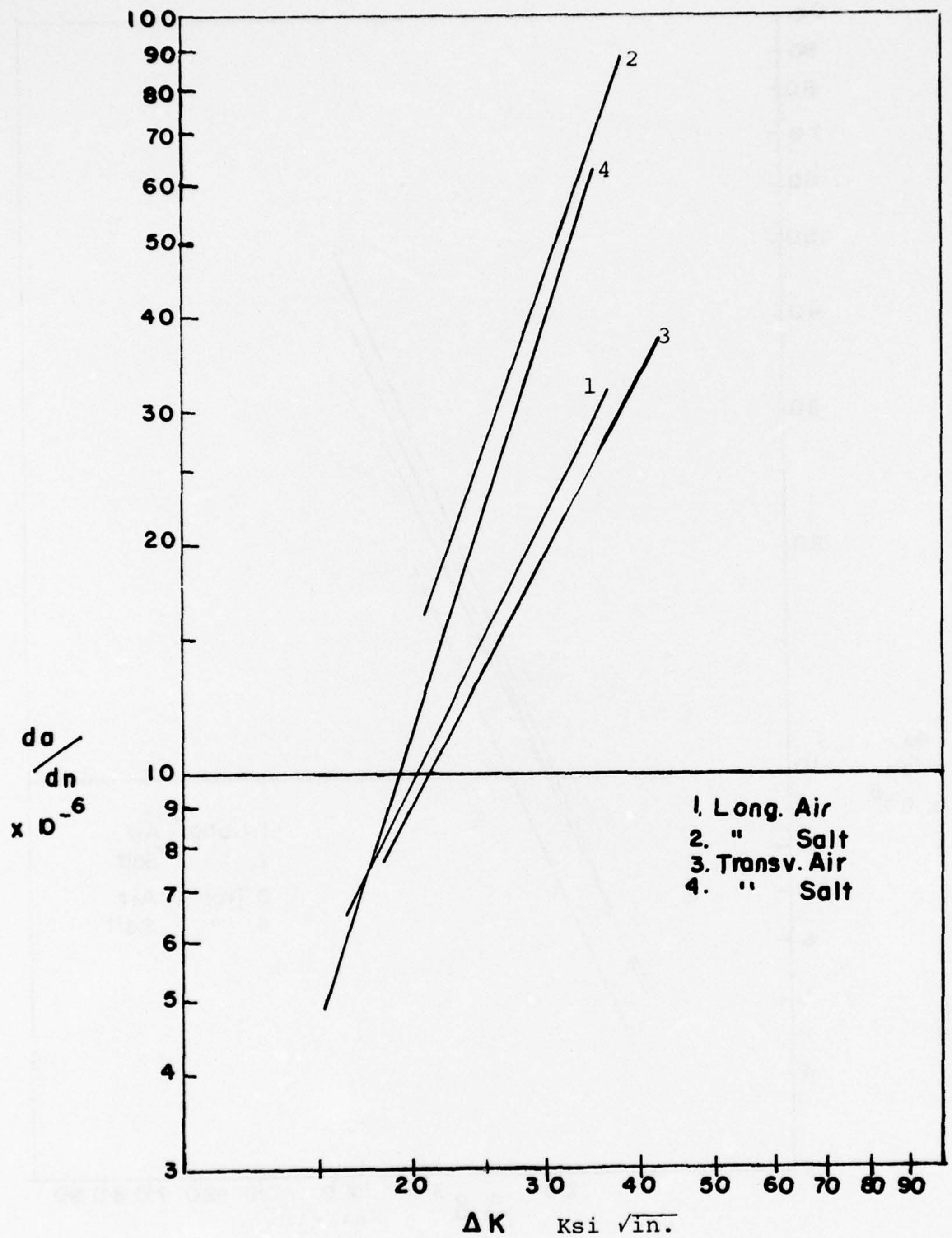

FIGURE 44. Crack Growth for 0.100" Gage Lab Rolled Strip Ti-8V-4Cr-2Mo-2Fe-3Al Alloy

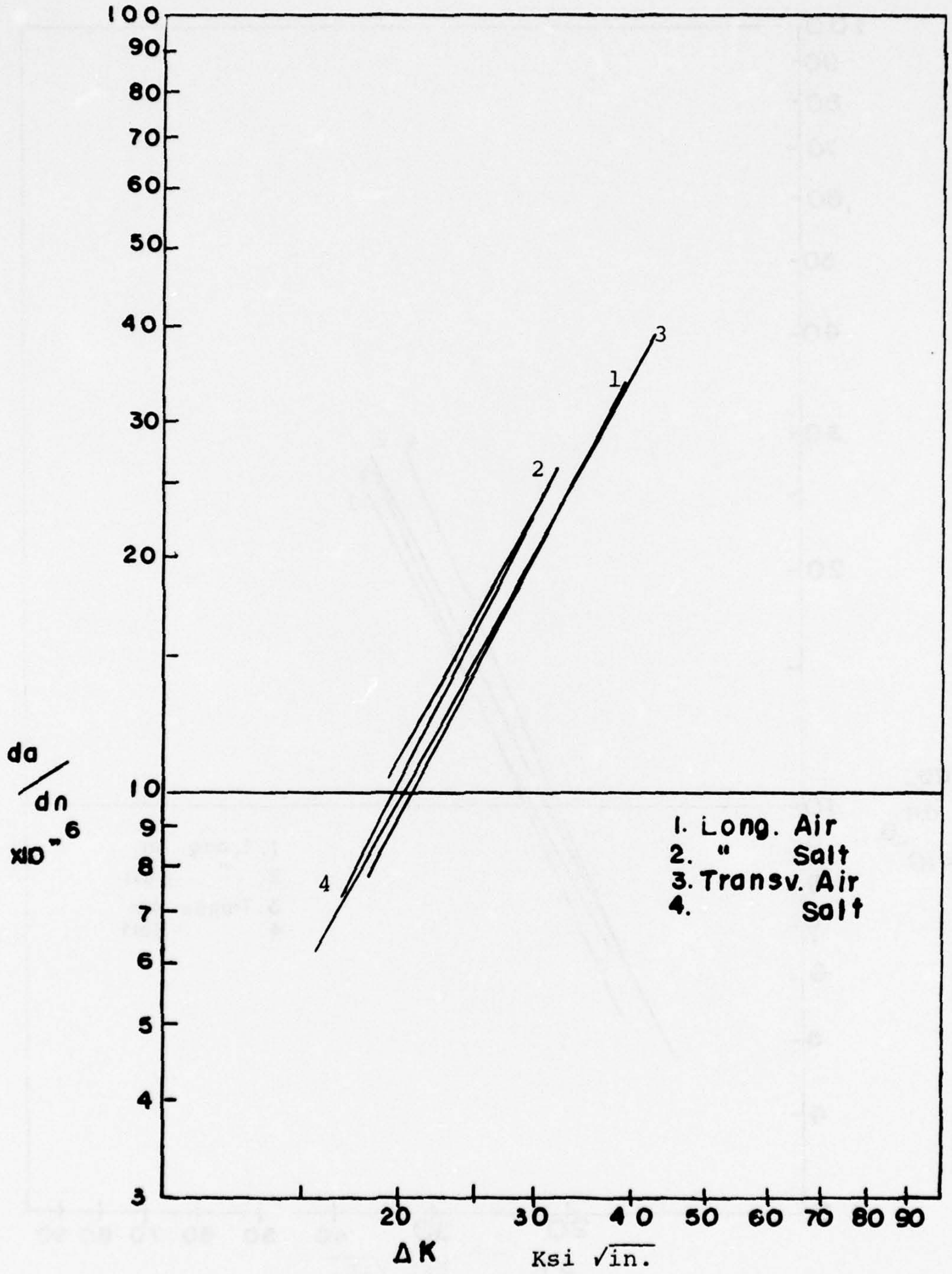

FIGURE 45. Crack Growth for 0.100" Gage Lab Rolled Strip Ti-15V-3Cr-3Al-3Sn Alloy

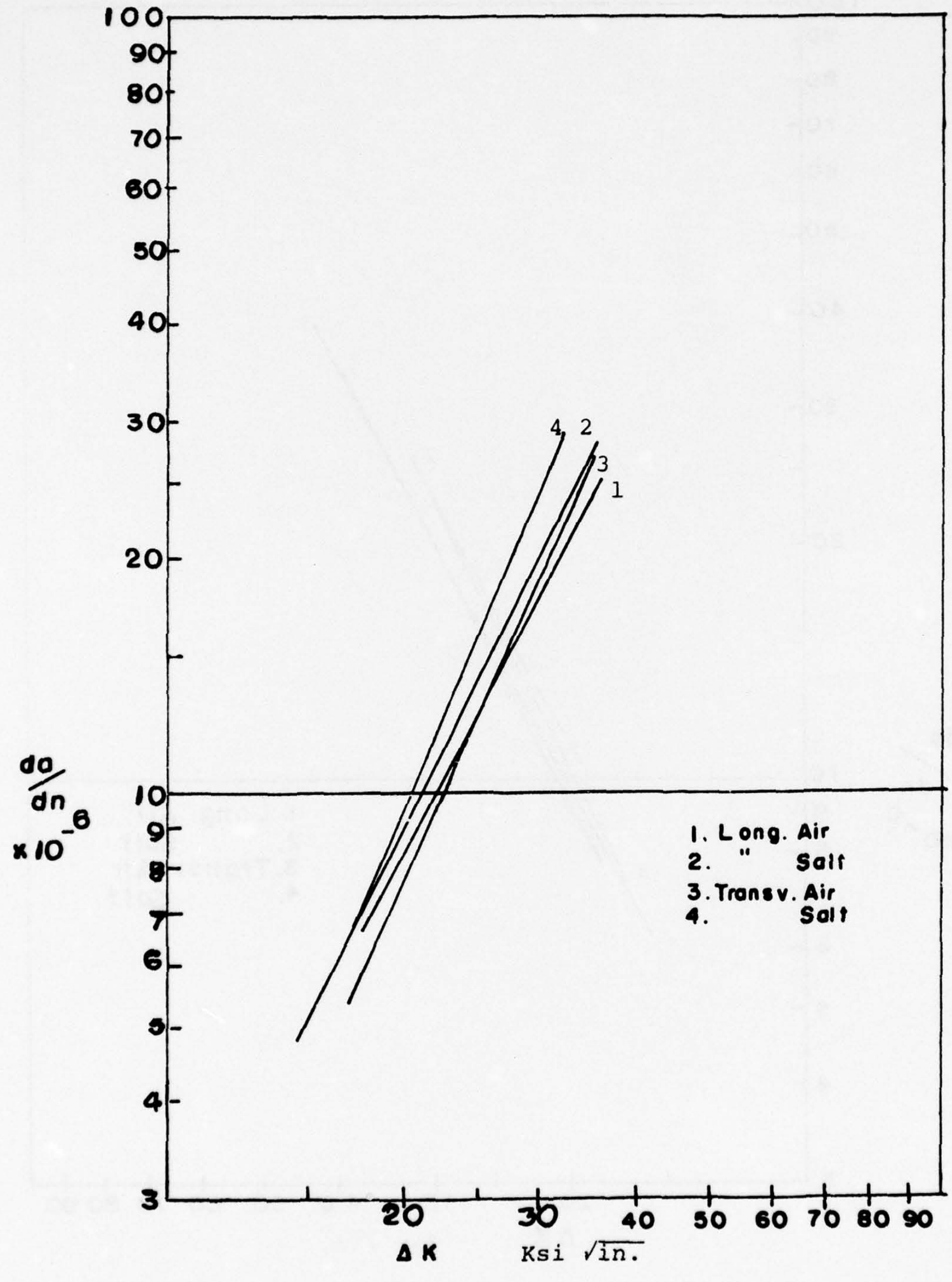

FIGURE 46. Crack Growth for 0.050" Gage Sheet Rolled Strip Ti-8V-7Cr-3Al-4Sn-1Zr Alloy

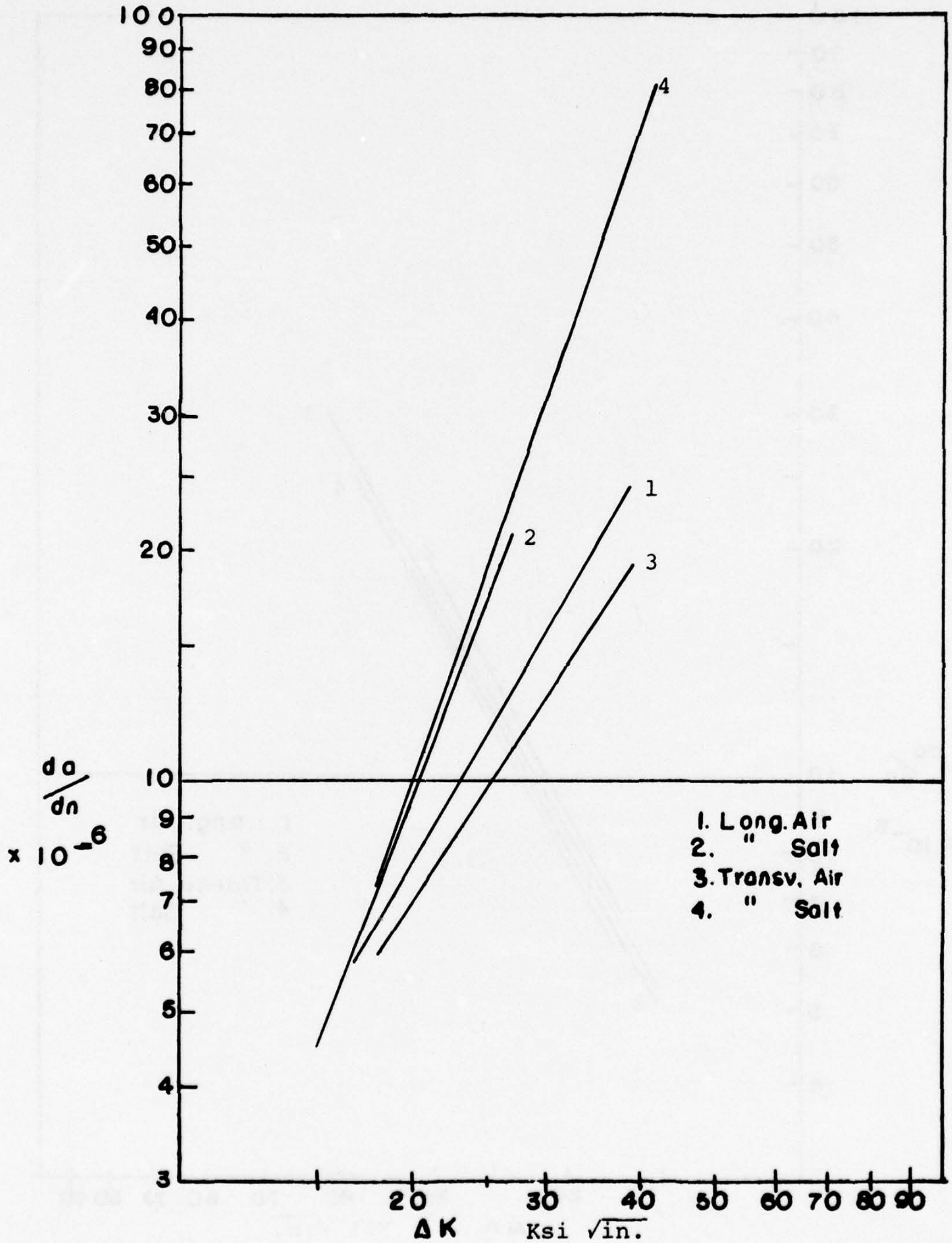

FIGURE 47. Crack Growth for 0.050" Gage Sheet Rolled Strip Ti-8V-4Cr-2Mo-2Fe-3Al Alloy

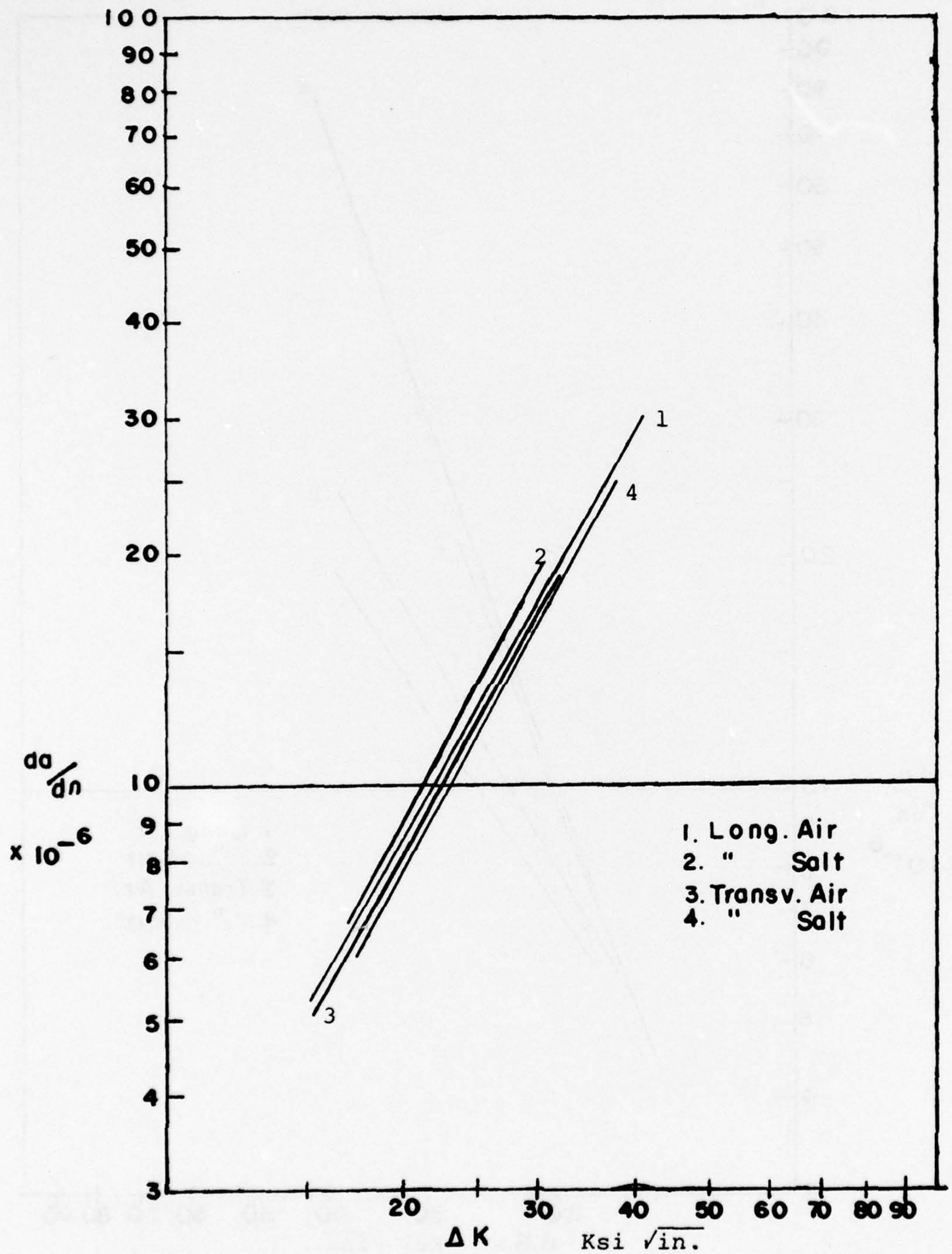

FIGURE 48. Crack Growth for 0.050" Gage Sheet Rolled Strip Ti-15V-3Cr-3Al-3Sn Alloy

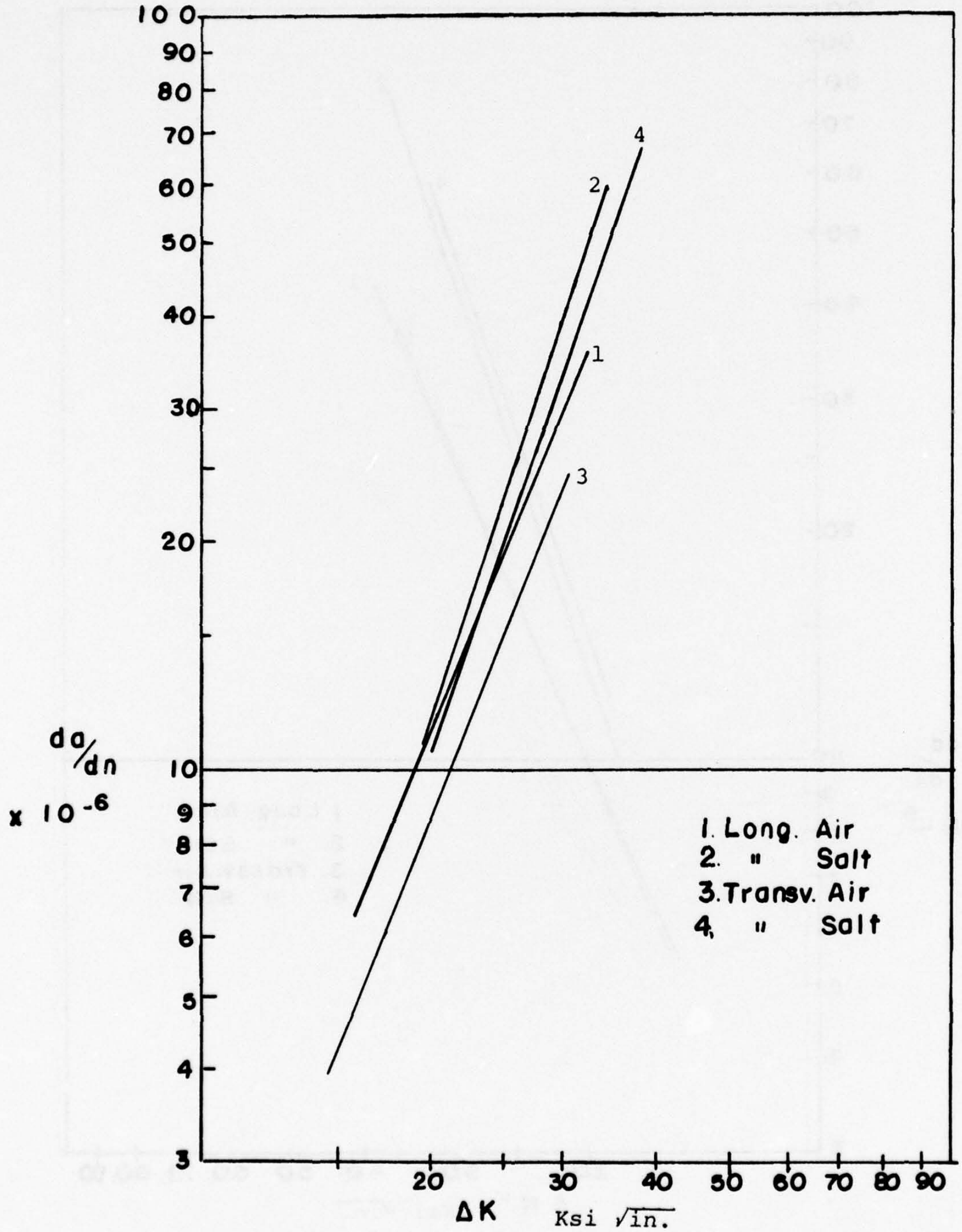

FIGURE 49. Crack Growth for 0.100" Gage Sheet Rolled Strip Ti-8V-7Cr-3Al-4Sn-1Zr Alloy

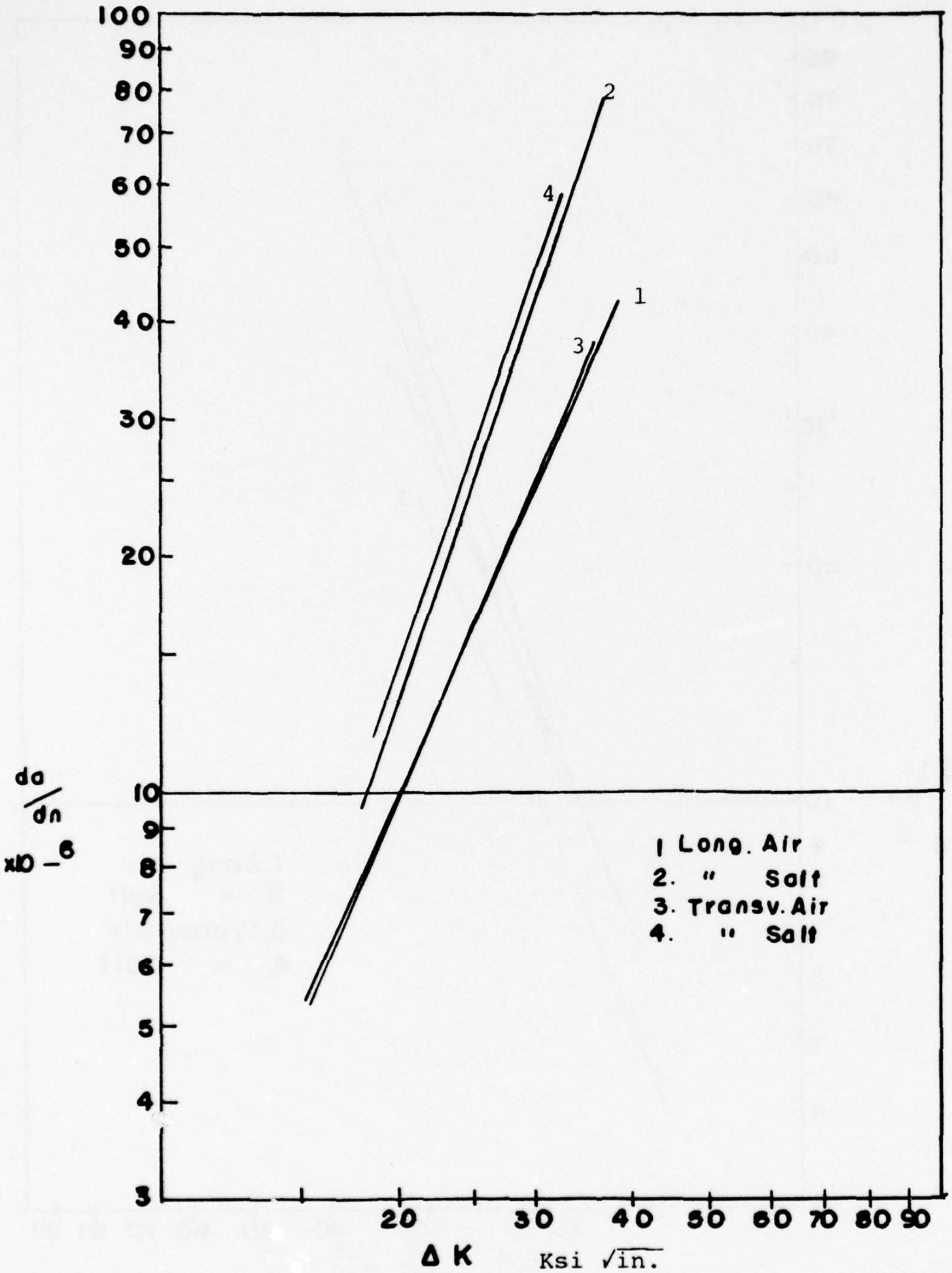

FIGURE 50. Crack Growth for 0.100" Gage Sheet Rolled Strip Ti-8V-4Cr-2Mo-2Fe-3Al Alloy

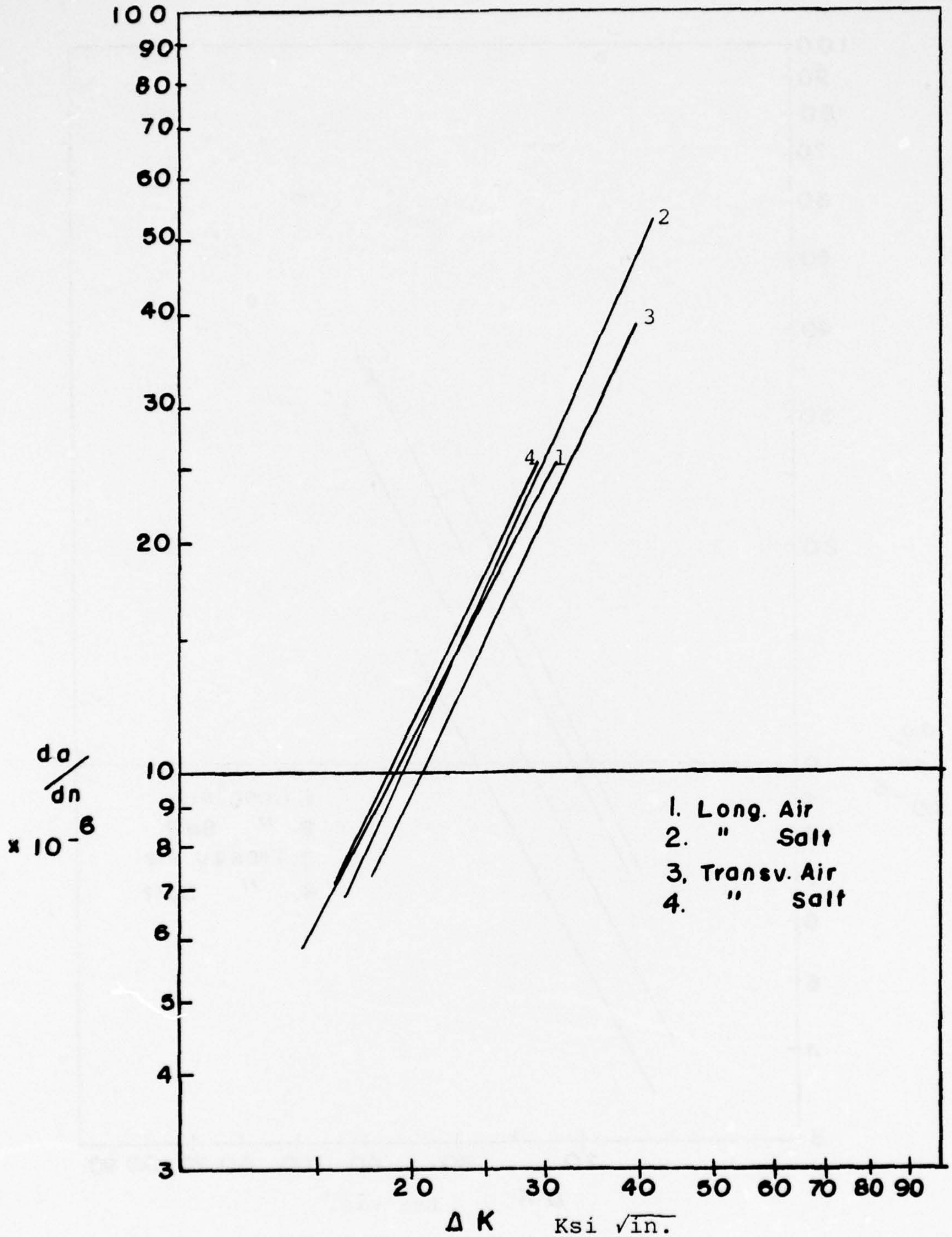

FIGURE 51. Crack Growth for 0.100" Gage Sheet Rolled Strip Ti-15V-3Cr-3Al-3Sn Alloy

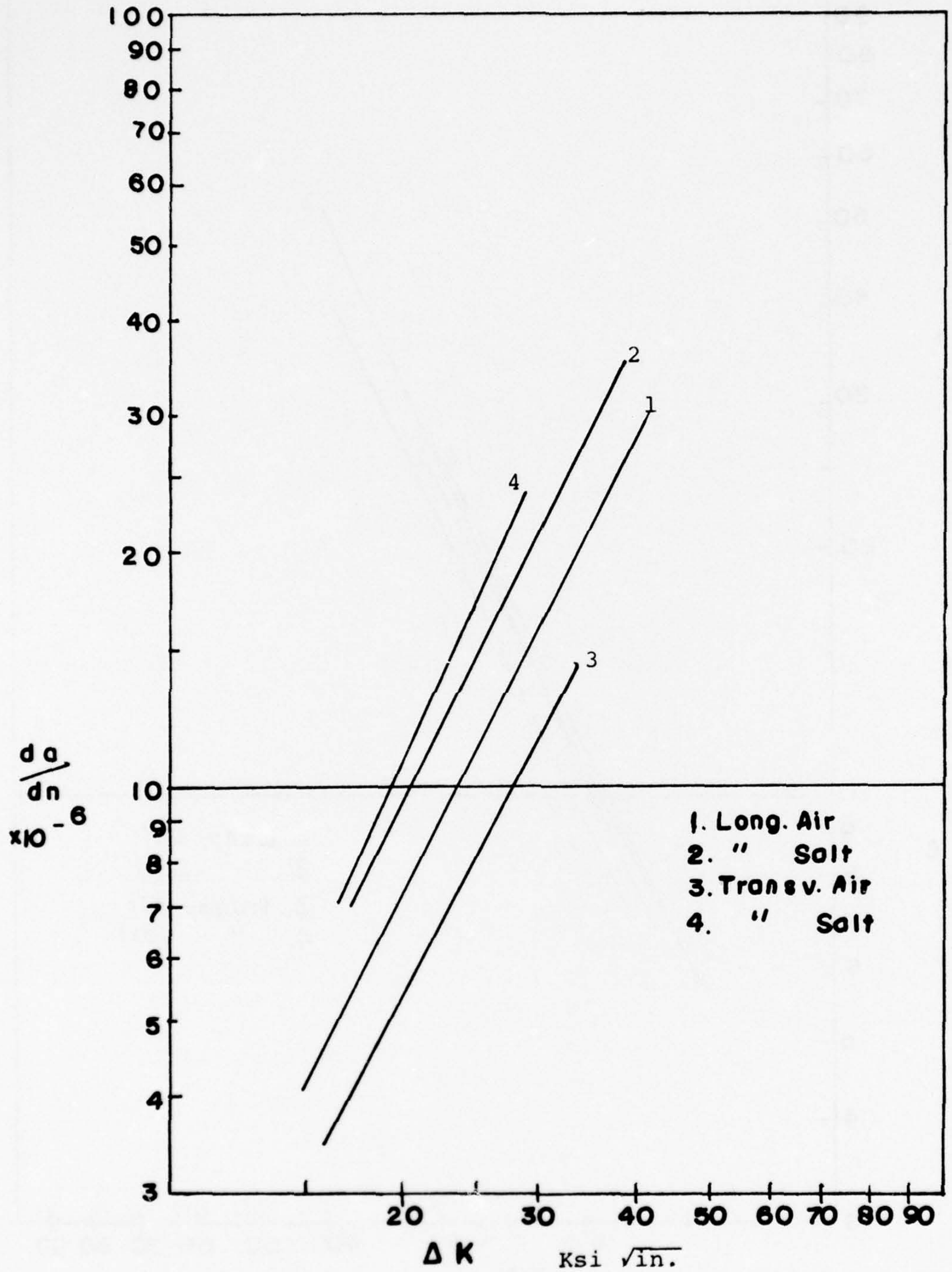

FIGURE 52. Crack Growth for 0.050" Gage
Hot + Cold Rolled Sheet Ti-8V-7Cr-3Al-4Sn-1Zr Alloy

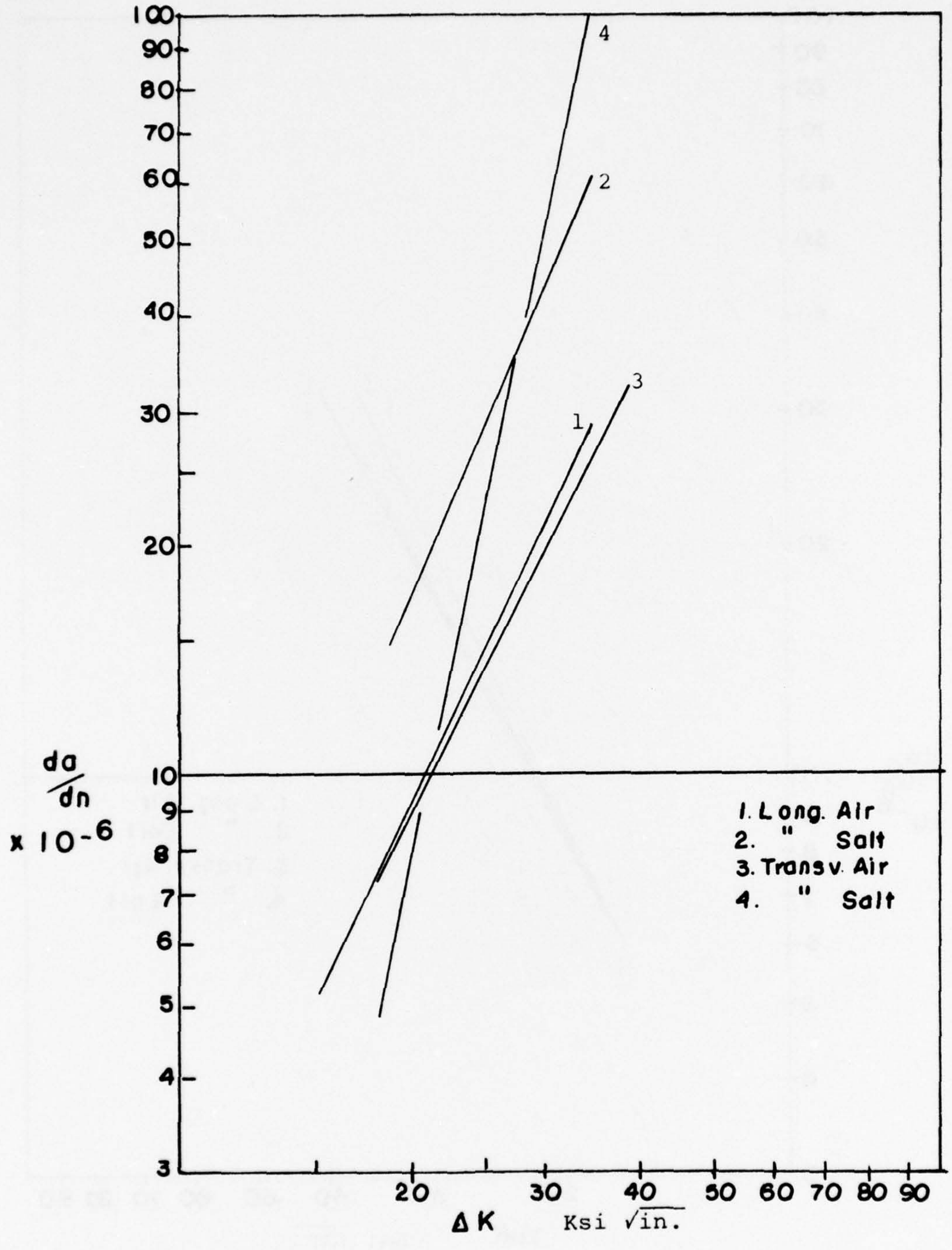

FIGURE 53. Crack Growth for 0.050" Gage
Hot + Cold Rolled Sheet Ti-8V-4Cr-2Mo-2Fe-3Al Alloy

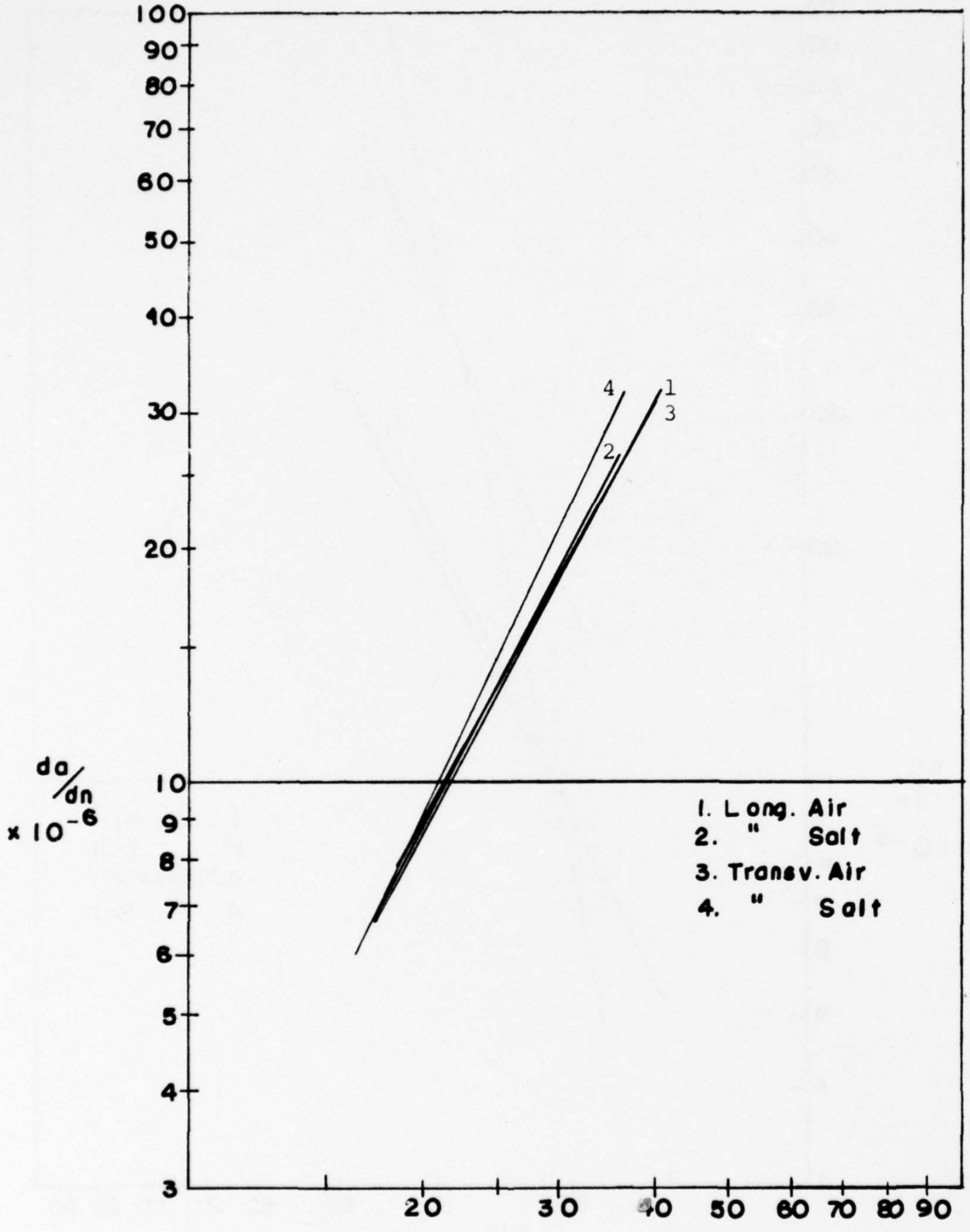

FIGURE 54. Crack Growth for 0.050" Gage
Hot + Cold Rolled Sheet Ti-15V-3Cr-3Al-3Sn Alloy

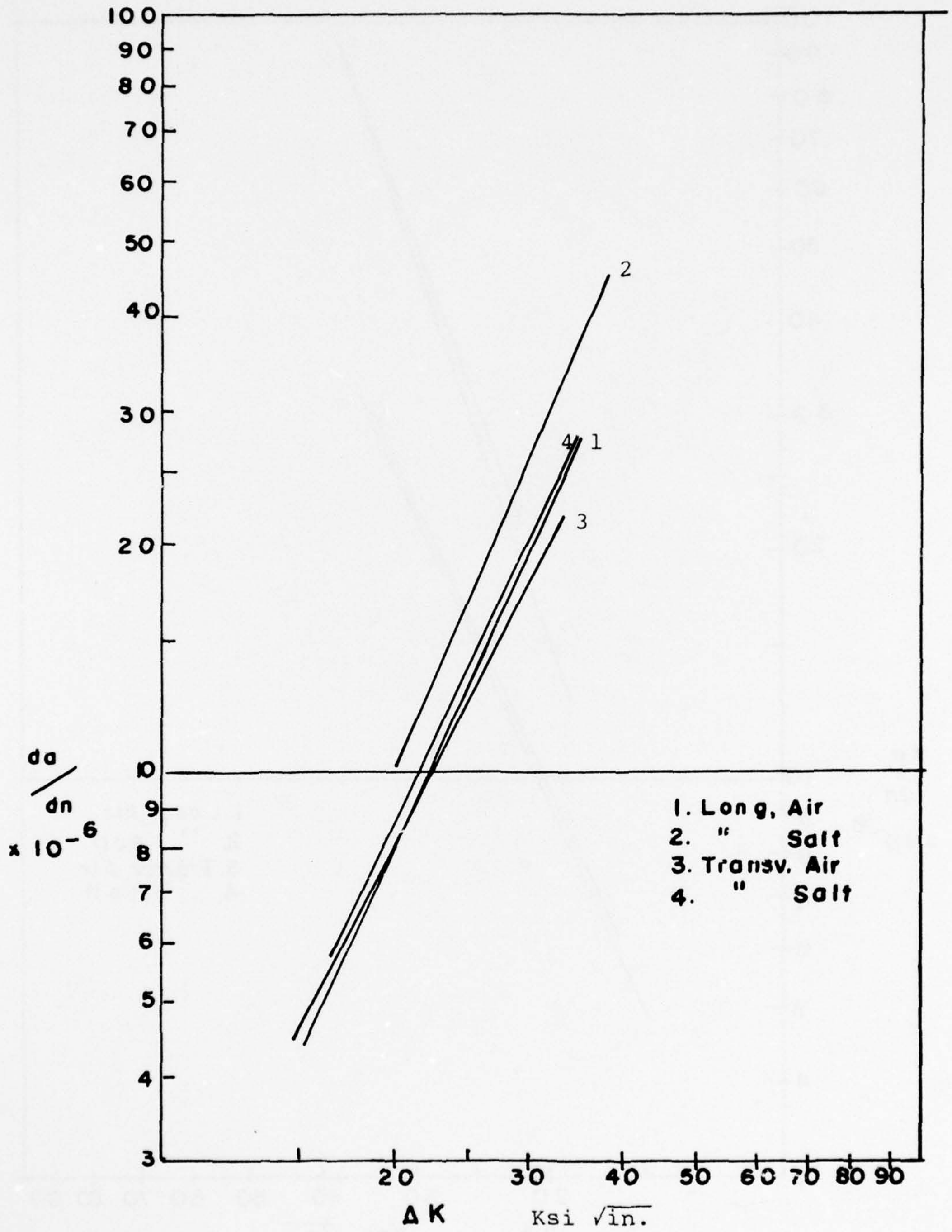

FIGURE 55. Crack Growth for 0.100" Gage Hot + Cold Rolled Sheet Ti-8V-7Cr-3Al-4Sn-1Zr Alloy

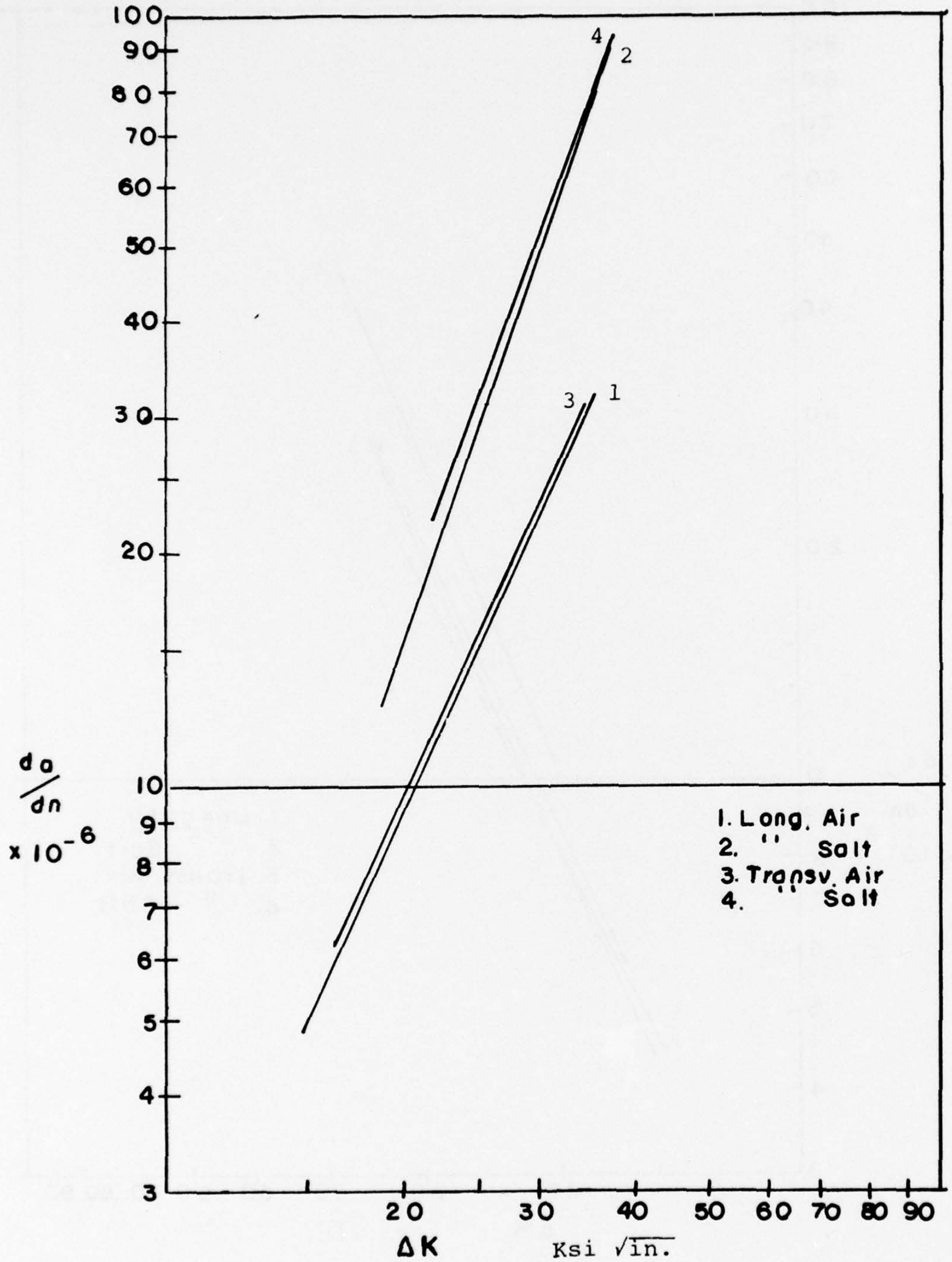

FIGURE 56. Crack Growth for 0.100" Gage
Hot + Cold Rolled Sheet Ti-8V-4Cr-2Mo-2Fe-3Al Alloy

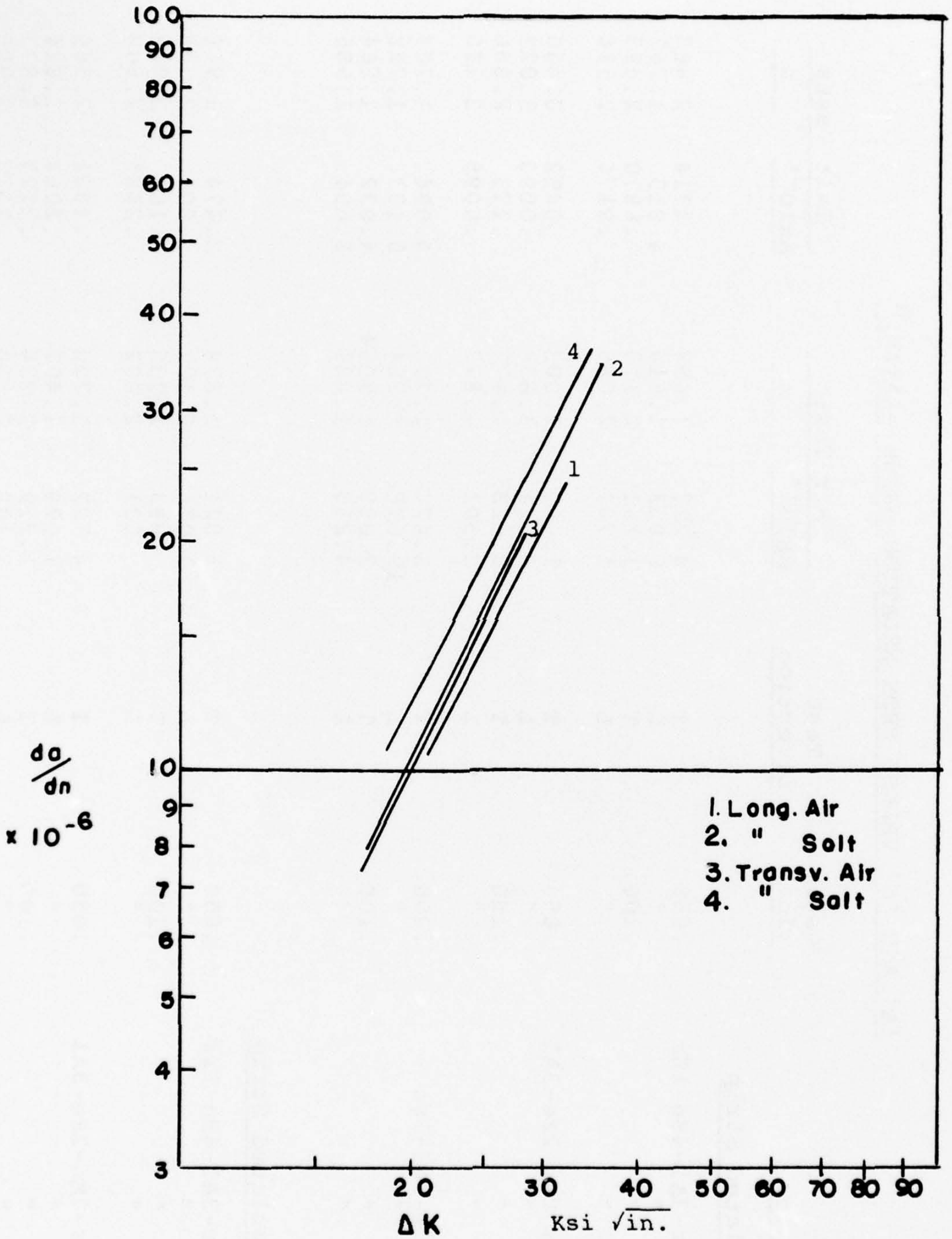

FIGURE 57. Crack Growth for 0.100" Gage
Hot + Cold Rolled Sheet Ti-15V-3Cr-3Al-3Sn Alloy

TABLE 19

'A' AND 'n' VALUES FROM RELATION $da/dn = A(\Delta K)^n$

Alloy	Gage, In.	Test Direction	Air Tests $Ax10^{-8}$	Air Tests n	Salt Tests $Ax10^{-8}$	Salt Tests n
Lab Simulated Strip						
Ti-8V-7Cr-3Al-4Sn-1Zr	.050	T	4.227	1.698	.4714	2.663
"	"	L	6.853	1.614	4.815	1.757
"	.100	T	1.251	2.125	.6870	2.423
"	"	L	1.787	2.086	.9176	2.316
Ti-8V-4Cr-2Mo-2Fe-3Al	.050	T	1.690	2.003	.0452	3.430
"	"	L	3.021	1.834	.0093	3.029
"	.100	T	2.623	1.977	.273	2.856
"	"	L	3.301	1.872	.0099	3.120
Ti-15V-3Cr-3Al-3Sn	.050	T	3.474	1.793	4.094	1.783
"	"	L	19.678	1.284	5.133	1.722
"	.100	T	3.088	1.9064	4.032	1.864
"	"	L	4.213	1.821	2.694	1.985
Sheet Simulated Strip						
Ti-8V-7Cr-3Al-4Sn-1Zr	.050	T	3.021	1.874	2.474	1.968
"	"	L	1.076	2.192	.806	2.358
"	.100	T	.993	2.335	.165	2.949
"	"	L	.631	2.402	.2385	2.803
Ti-8V-4Cr-2Mo-2Fe-3Al	.050	T	4.722	1.700	.4331	2.569
"	"	L	7.929	1.497	.2064	2.824
"	.100	T	1.219	2.234	.2327	2.877
"	"	L	1.108	2.260	.2312	2.905

-continued-

TABLE 19 - continued

Alloy	Gage, In.	Test Direction	Air Tests $Ax10^{-8}$	Air Tests n	Salt Tests $Ax10^{-8}$	Salt Tests n
Sheet Simulated Strip						
Ti-15V-3Cr-3Al-3Sn	.050	T	4.961	1.716	3.385	1.849
"	"	L	4.061	1.760	3.374	1.812
"	.100	T	3.309	1.932	1.523	2.182
"	"	L	1.970	2.053	2.007	2.083
Hot + Cold Rolled						
Ti-8V-7Cr-3Al-4Sn-1Zr	.050	T	2.446	1.906	2.359	1.999
"	"	L	2.177	1.841	1.426	2.214
"	.100	T	1.117	2.189	1.152	2.259
"	"	L	2.412	1.928	1.612	2.088
Ti-8V-4Cr-2Mo-2Fe-3Al	.050	T	1.752	2.095	1.686	2.310
"	"	L	2.431	1.963	.0010	4.543
"	.100	T	1.485	2.147	.339	2.805
"	"	L	1.550	2.144	.595	2.671
Ti-15V-3Cr-3Al-3Sn	.050	T	3.325	1.852	2.996	1.892
"	"	L	3.988	1.802	1.800	2.075
"	.100	T	2.685	2.957	2.240	2.051
"	"	L	1.910	2.089	3.396	1.964

TABLE 20

CRACK GROWTH RATES FOR SELECTED ΔK VALUES
'A' AND 'n' VALUES FROM RELATION $da/dn = A(\Delta K)^n$

Alloy	Gage, In.	Test Direction	da/dn, In. x 10^{-6} at $\Delta K = 20$ Air A	at $\Delta K = 20$ Salt n	at $\Delta K = 40$ $Ksi\sqrt{in}$ Air A	at $\Delta K = 40$ $Ksi\sqrt{in}$ Salt n
Lab Simulated Strip						
Ti-8V-7Cr-3Al-4Sn-1Zr	.050	T	6.9	10.35	22 *	86 *
"	"	L	8.4	9.2	26.5*	32 *
"	.100	T	7.2	10	35 *	56 *
"	"	L	9.4	9.4	40 *	48 *
Ti-8V-4Cr-2Mo-2Fe-3Al	.050	T	6.7	13	28.7	103 *
"	"	L	7.3	7.8	27.0	69 *
"	.100	T	9.6*	14	38 *	98 *
"	"	L	9.0	11.2	34	94 *
Ti-15V-3Cr-3Al-3Sn	.050	T	7.4	8.6	26.2*	29.5*
"	"	L	9.2	8.9	23.0*	29.5*
"	.100	T	9.7	11	36 *	39 *
"	"	L	9.2	10	34	40 *
Sheet Simulated Strip						
Ti-8V-7Cr-3Al-4Sn-1Zr	.050	T	8.3	9	31 *	36 *
"	"	L	7.8	9.5	36 *	49 *
"	.100	T	11	11.5	59 *	93 *
"	"	L	8.5	10.5	48 *	75 *

-continued-

TABLE 20 - continued

Alloy	Gage, In.	Test Direction	da/dn, In. x 10^{-6} at $\Delta K = 20$ Air A	at $\Delta K = 20$ Salt n	at $\Delta K = 40$ Ksi$\sqrt{in}$ Air A	at $\Delta K = 40$ Ksi$\sqrt{in}$ Salt n
Sheet Simulated Strip						
Ti-8V-4Cr-2Mo-2Fe-3Al	.050	T	7.8	9.4	26	58 *
"	"	L	7	10	20	70
"	.100	T	9.8	13	47 *	100 *
"	"	L	9.9	14.5	49 *	107 *
Ti-15V-3Cr-3Al-3Sn	.050	T	8.5	8.9	28	32 *
"	"	L	8	7.8	27 *	27 *
"	.100	T	11	10.5	42 *	48
"	"	L	9.2	11.5	39	48 *
Hot + Cold Rolled						
Ti-8V-7Cr-3Al-4Sn-1Zr	.050	T	7.2	9.4	28	38 *
"	"	L	5.2	10.7	19.5*	49.5*
"	.100	T	8.0	10	35	48 *
"	"	L	8.0	8.5	30.5*	36
Ti-8V-4Cr-2Mo-2Fe-3Al	.050	T	9.2	17.2	39 *	86 *
"	"	L	8.9	7.7	34 *	216 *
"	.100	T	9.2	15	41 *	114 *
"	"	L	9.6	17.5*	43 *	114 *
Ti-15V-3Cr-3Al-3Sn	.050	T	8.8	8.9	32	33 *
"	"	L	8.9	9.1	32	39 *
"	.100	T	9.5*	10.2	37 *	43 *
"	"	L	10.0	12.3	42 *	48 *

*Extrapolated

Comparing the da/dn vs. ΔK results in the figures and tables, the difference between alloys was not large. The Ti-15V-3Cr-3Al-3Sn alloy showed less effect of directionality and salt water than the other two alloys for all conditions. Generally, the 0.050" gage had lower crack growth rates than 0.100" gage for all alloys and processing conditions.

Comparison of the crack growth rates for these alloys with those for Ti-6Al-4V hand mill sheet[7] showed lower growth rates for the present beta alloys.

6. Thermal and Dimensional Stability

Thermal and dimensional stability results for a 600F-150hr exposure of aged materials are shown in Table 21. These dimensional stability results were obtained using a model number 673 Starrett precision micrometer calibrated in 0.00005" divisions and measurements were over a 0.50" length whose edges had been precision milled.

Tensile properties after exposure and dimensional changes during the exposure are shown. The tensile properties show acceptable as exposed strengths and ductilities. For the Ti-15V-3Cr-3Al-3Sn alloy 0.100" gage strip condition transverse tensile elongation in the lab strip decreased from approximately 15 to 5 per cent; but this sample had a ductile fracture, and the location of the fracture near the gage mark would account for the low elongation value. Unexposed tensile properties are given in the tables in Figures 22 through 39 where "RD" is longitudinal and "TD" is transverse. Comparison of properties before and after exposure shows three cases of increased yield strength. One is a 20 Ksi increase for the Ti-15V-3Cr-3Al-3Sn sample noted above. The second is for the Ti-8V-7Cr-3Al-4Sn-1Zr alloy 0.100" gage sheet simulated strip in the transverse direction where elongation decreased from 19 to 11 per cent. The third was for the Ti-8V-4Cr-2Mo-2Fe-3Al alloy 0.100" gage hot plus cold rolled sheet longitudinal direction where elongation decreased from 16 to 14 per cent. Some of these strength differences between exposed and unexposed conditions may arise from the aging treatments also.

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[7] Damage Tolerant Design Handbook, MCIC HB-01, Jan.1975.

TABLE 21

THERMAL AND DIMENSIONAL STABILITY AFTER 600F-150 HR. EXPOSURE OF SOLUTION TREATED AND AGED MATERIALS

Alloy	Gage, In.	Test Direction	Tensile Properties TS, Ksi	YS, Ksi	El, %	Dimensional Change,[1] .001-in./in.
Laboratory Simulated Strip						
Ti-8V-7Cr-3Al-4Sn-1Zr	.050	L	161	149	11	- .30
"	"	T	162	148	15	.50
"	.100	L	165	151	13	- .70
"	"	T	165	152	13	.10
Ti-8V-4Cr-2Mo-2Fe-3Al	.050	L	168	158	11	.20
"	"	T	169	157	11	1.6
"	.100	L	171	158	12	1.0
"	"	T	173	161	14	- .1
Ti-15V-3Cr-3Al-3Sn	.050	L	173	159	11	.5
"	"	T	174	158	12	.6
"	.100	L	172	156	12	-1.7
"	"	T	192	176	5[3]	[2]
Sheet Simulated Strip						
Ti-8V-7Cr-3Al-4Sn-1Zr	.C50	L	173	158	15	-1.9
"	"	T	173	158	13	-1.8
"	.100	L	168	155	15	-3
"	"	T	175	161	11	-5.6
Ti-8V-4Cr-2Mo-2Fe-3Al	.050	L	163	156	12	- .7
"	"	T	167	156	11	- .4
"	.100	L	170	162	10	-1.2
"	"	T	167	159	12	-2.7

-continued-

TABLE 21 - continued

Alloy	Gage, In.	Test Direction	Tensile Properties TS, Ksi	YS, Ksi	El, %	Dimensional Change,[1] .001-in./in.
Sheet Simulated Strip						
Ti-15V-3Cr-3Al-3Sn	.050	L	170	154	12	-4.7
"	"	T	172	155	14	-2.5
"	.100	L	176	161	8	-3.9
"	"	T	184	168	8	-1.5
Hot + Cold Rolled Sheet						
Ti-8V-7Cr-3Al-4Sn-1Zr	.050	L	173	156	14	- .80
"	"	T	178	168	9	-1.90
"	.100	L	158	147	19	-2.7
"	"	T	157	146	21	-5.0
Ti-8V-4Cr-2Mo-2Fe-3Al	.050	L	174	164	11	-1.3
"	"	T	176	167	9	- .10
"	.100	L	175	165	14	- .90
"	"	T	182	171	12	-3.4
Ti-15V-3Cr-3Al-3Sn	.050	L	177	162	11	-1.3
"	"	T	180	166	11	-1.8
"	.100	L	174	159	15	-1.3
"	"	T	171	157	15	-2.2

[1]Shrinkage indicated by (-) sign, otherwise change was expansion.
[2]Original measurement was incorrect.
[3]Fractured near gage mark.

Dimensional changes show larger variations for processing conditions than between alloys. The lab simulated strip material showed less change than for sheet rolled materials. The Ti-8V-7Cr-3Al-4Sn-1Zr alloy lab strip produced showed the best dimensional stability.

7. Phase Identification

Phase identification results are shown in summary in Table 22. The lines observed could all be indexed to alpha or beta titanium for this over-aged, 1100F-24hr, condition of heat treatment except for two lines in the lab simulated strip of Ti-8V-7Cr-3Al-4Sn-1Zr alloy. These could not be indexed to any known titanium material and are possibly associated with sample preparation or other. Results for all six conditions for each of the three alloys were obtained but are not shown because 2Θ and 'd' spacings results were similar to those shown. A rotating specimen holder was used with Cu Kα radiation.

TABLE 22

PHASE IDENTIFICATION BY X-RAY FOR ALLOY SAMPLES OVERAGED AT 1100F - 24 HRS.

Alloy	Gage, In.	Phase	$2\theta^{\circ 1}$	d Spacing, Å
Ti-8V-7Cr-3Al-4Sn-1Zr Lab Simulated Strip	.050	α	35.1	2.56
		α	38.18	2.36
		β	39.62	2.27
		α	40.15	2.24
		-	46.9	1.94
		-	49.65	1.84
		α	52.9	1.73
		β	57.32	1.61
		α	63.1	1.47
		α	70.4	1.34
		β	72.0	1.31
Ti-8V-7Cr-3Al-4Sn-1Zr Lab Simulated Strip	.100	α	35.18	2.55
		α	38.25	2.36
		β	39.7	2.27
		α	40.25	2.24
		α	53.0	1.74
		β	57.4	1.60
Ti-8V-7Cr-3Al-4Sn-1Zr Sheet Simulated Strip	.050	α	35.4	2.53
		α	38.5	2.34
		β	39.9	2.26
		α	40.45	2.23
		α	53.17	1.72
		β	57.55	1.60
Ti-8V-7Cr-3Al-4Sn-1Zr Sheet Simulated Strip	.100	α	35.2	2.55
		α	38.3	2.35
		β	39.75	2.27
		α	40.25	2.24
		α	53.05	1.73
		β	57.4	1.60

TABLE 22 - continued

Alloy	Gage, In.	Phase	$2\theta^{\circ}$[1]	d Spacing, Å
Ti-8V-4Cr-2Mo-2Fe-3Al Lab Simulated Strip	.050	α	35.25	2.54
		α	38.32	2.35
		β	39.7	2.27
		α	40.28	2.24
		α	53.12	1.72
		β	57.47	1.60
Ti-8V-4Cr-2Mo-2Fe-3Al Lab Simulated Strip	.100	α	35.35	2.54
		α	38.47	2.34
		β	39.81	2.26
		α	40.41	2.23
		α	53.25	1.72
		β	57.55	1.60
Ti-15V-3Cr-3Al-3Sn Lab Simulated Strip	.050	α	35.13	2.55
		α	38.25	2.35
		β	39.62	2.27
		α	40.18	2.24
		α	53.0	1.73
		β	57.35	1.61
Ti-15V-3Cr-3Al-3Sn Lab Simulated Strip	.100	α	35.29	2.54
		α	38.38	2.34
		β	39.77	2.27
		α	40.38	2.23
		α	53.23	1.72
		β	57.53	1.60

[1]Cu Kα radiation with rotating specimen.

SECTION IV

PHASE III

A. FORMABILITY EVALUATION

The formability evaluation of the three alloys was intended to supply information on the concept of room temperature forming in the solution annealed condition followed by aging of a formed part with a mild restraint or preferably no restraint at all. Up to this point the other objectives of the Summary Workshop had been met and the three alloys had been shown to have superior property-density relations to other titanium materials available.

The formability results described were obtained in TIMET laboratories and in Rockwell International's Columbus, Ohio, facility. These latter results are described in Appendix A.

1. Bend Deflection

Bend deflection results are shown in Table 23 for 45° and 135° included angles. Complex parts can involve several bend angles so both angles were included. The average springback at 45° was slightly larger for the Ti-8V-7Cr-3Al-4Sn-1Zr alloy than for the other two. At 135° the average was slightly larger for the Ti-15V-3Cr-3Al-3Sn alloy and least for the Ti-8V-7Cr-3Al-4Sn-1Zr alloy. The differences of 1 to 3° here are open to question and other forming considerations may possibly override these. No results were obtained for laboratory simulated strip processed material here. Laboratory simulated strip was not included here because it would be expected to be close to sheet simulated strip. Greater variation was expected and found from the use of two bend angles.

TABLE 23

BEND DEFLECTION RESULTS

Alloy	Gage, In.	Test Direction	Springback, Degrees for Bend Angle Indicated 45°	135°
Sheet Simulated Strip				
Ti-8V-7Cr-3Al-4Sn-1Zr	.050	L	20	4.8
"	"	T	20.8	3
"	.100	L	23	9
"	"	T	27.5	6.5
Ti-8V-4Cr-2Mo-2Fe-3Al	.050	L	22	7.5
"	"	T	20.8	9.5
"	.100	L	22	8
"	"	T	21	7.3
Ti-15V-3Cr-3Al-3Sn	.050	L	22	7
"	"	T	20.5	8.3
"	.100	L	23.5	12
"	"	T	22.5	12.5
Hot + Cold Rolled Sheet				
Ti-8V-7Cr-3Al-4Sn-1Zr	.050	L	25.5	10
"	"	T	25	10.8
"	.100	L	21.3	7
"	"	T	23	6.8

-continued-

TABLE 23 - continued

Alloy	Gage, In.	Test Direction	Springback, Degrees for Bend Angle Indicated 45°	135°
Ti-8V-4Cr-2Mo-2Fe-3Al	.050	L	22.8	10.3
"	"	T	22.5	9
"	.100	L	21.5	7.8
"	"	T	22.8	8
Ti-15V-3Cr-3Al-3Sn	.050	L	23	8.8
"	"	T	21.8	9.8
"	.100	L	22.3	7.5
"	"	T	21.5	7

2. <u>Olsen Cup Tests</u>

Olsen cup test results are shown in Table 24. These values are equal to or better than published data on existing titanium materials.(7) The differences obtained between averages for the alloys is almost insignificant nor was there a significant difference introduced from processing.

3. <u>Deflection from Aging Bend Samples</u>

Deflection from aging bend sample results are shown in Table 25. For this test 1" wide samples were bent 90° to ~3.5xT in the solution annealed condition. The samples were then placed in an angle iron with a 1/2" steel rod placed in the bend I.D. to simulate mild restraint. The deflection is the angular difference between the legs of the bend before and after aging. The Ti-8V-4Cr-2Mo-2Fe-3Al alloy showed the least deflection, whereas, the Ti-8V-7Cr-3Al-4Sn-1Zr had the largest with up to 1-1/4 degrees opening of the bend angle. The results of this test are difficult to scale up in terms of a large part with complex angles, however, so the actual significance of 1/2 and 1° differences is subject to question. Considering the light restraint there was relatively little distortion. Probably the balance of the competing age hardening and stress relieving reactions was favorable for this aging cycle.

Cold work in annealed beta alloys is known to increase strength response to aging. Since high strength levels could give embrittlement, it was considered important to assess this possibility. The approach used was to section the bend specimens used for restraint and determine Knoop Hardness at the tension and compression sides of the bend and at the mid thickness point.

The hardness values obtained for 0.050" gage and 0.100" gage are shown in Table 26. The yield strength and elongation values shown with the hardness values were obtained from a correlation of strength and elongation with hardness. Minimum elongation values extrapolated in this manner were 6" for the 0.050" gage and 7" for the 0.100" gage which appear acceptable for most structural materials.

TABLE 24

OLSEN CUP TEST RESULTS

Alloy	Gage, In.	Olsen Cup-Depth at Failure, In.	Ram Load at Failure, Lbs.
Laboratory Simulated Strip			
Ti-8V-7Cr-3Al-4Sn-1Zr	.050	.39	11,600
"	.100	.49	28,000
Ti-8V-4Cr-2Mo-2Fe-3Al	.050	.35	11,000
"	.100	.44	25,900
Ti-15V-3Cr-3Al-3Sn	.050	.34	10,000
"	.100	.45	23,500
Sheet Simulated Strip			
Ti-8V-7Cr-3Al-4Sn-1Zr	.050	.36	14,000
"	.100	.40	22,600
Ti-8V-4Cr-2Mo-2Fe-3Al	.050	.39	13,500
"	.100	.48	26,700
Ti-15V-3Cr-3Al-3Sn	.050	.39	13,400
"	.100	.44	24,000
Hot + Cold Rolled Sheet			
Ti-8V-7Cr-3Al-4Sn-1Zr	.050	.31	10,800
"	.100	.46	26,800
Ti-8V-4Cr-2Mo-2Fe-3Al	.050	.35	12,600
"	.100	.41	23,600
Ti-15V-3Cr-3Al-3Sn	.050	.35	11,000
"	.100	.47	25,200

TABLE 25

DEFLECTION FROM AGING FOR LIGHTLY RESTRAINED BEND SAMPLES OF LABORATORY SIMULATED STRIP

Alloy	Test Direction	Age Treatment Temp, F	Age Treatment Time, Hrs	Deflection, Degrees Side 1	Deflection, Degrees Side 2	Bend Radius
0.050" Gage[1]						
Ti-8V-7Cr-3Al-4Sn-1Zr	L	1050	8	0	1	3.0
"	T	"	"	+.50	+1.25	3.5
Ti-8V-4Cr-2Mo-2Fe-3Al	L	1050	16	<-.50	0[2]	3.5
"	T	"	"	0	0[2]	3.0
Ti-15V-3Cr-3Al-3Sn	L	1050	4	0	<-.50	3.0
"	T	"	"	-.50 to 1	<-.50	3.5
0.100" Gage[2]						
Ti-8V-7Cr-3Al-4Sn-1Zr	L	1050	8	+2	+2	3.5
"	T	"	"	+2	+1.50	3.5
Ti-8V-4Cr-2Mo-2Fe-3Al	L	1050	16	+1.50	+1.50	3.0
"	T	"	"	+1.50	+1.50	3.5
Ti-15V-3Cr-3Al-3Sn	L	1050	8	+<.50	+<.50	3.0
"	T	"	"	+<.50	+<.50	3.5

[1] '+' designates opening of bend, '-' designates closing of bend.
[2] Bowed leg after exposure.
Exposed in angle iron with 1/2" dia. rod in bend radius.

TABLE 26

EFFECT OF COLD WORK ON AGED PROPERTIES
AS MEASURED BY KNOOP HARDNESS FOR SIMULATED LAB STRIP

Alloy and Aging Treatment	Metal Condition	Tension Edge[1]			Center			Compression Edge[1]		
		KHN	YS,[2] Ksi	El,[2] %	KHN	YS,[2] Ksi	El,[2] %	KHN	YS,[2] Ksi	El,[2] %
0.050" Gage										
Ti-8V-7Cr-3Al-4Sn-1Zr Aged 1050°F-8hrs	Strained	359	183	6	359	183	6	335	167	8
"	Unstrained[3]	---	---	-	304	147	12	---	---	-
Ti-8V-4Cr-2Mo-2Fe-3Al Aged 1050°F-16hrs	Strained	352	177	8	359	182	7	352	177	8
"	Unstrained[3]	---	---	-	314	153	12	---	---	-
Ti-15V-3Cr-3Al-3Sn Aged 1050°F-8hrs	Strained	320	153	12	320	152	12	335	163	8
"	Unstrained[3]	---	---	-	311	146	12	---	---	-
0.100" Gage										
Ti-8V-7Cr-3Al-4Sn-1Zr Aged 1050°F-8hrs	Strained	339	171	8	339	171	8	345	175	7
"	Unstrained[3]	---	---	-	324	161	10	---	---	-
Ti-8V-4Cr-2Mo-2Fe-3Al Aged 1050°F-16hrs	Strained	349	175	8	352	177	8	363	184	7
"	Unstrained[3]	---	---	-	339	169	10	---	---	-

-continued-

TABLE 26 - continued

Alloy and Aging Treatment	Metal Condition	Tension Edge[1] KHN	Tension Edge[1] YS,[2] Ksi	Tension Edge[1] El,[2] %	Center KHN	Center YS,[2] Ksi	Center El,[2] %	Compression Edge[1] KHN	Compression Edge[1] YS,[2] Ksi	Compression Edge[1] El,[2] %
Ti-15V-3Cr-3Al-3Sn Aged 1050°F-8hrs	Strained	314	148	13	314	147	13	317	150	13
"	Unstrained[3]	---	---	-	300	136	14	---	---	-

[1]Tension, compression refer to outer and inner surfaces respectively, of a bend sample at 3.0 or 3.5 x t. Hardness impressions were approximately 0.0015" below surface.

[2]Yield strength and elongation values are derived from Knoop Hardness value.

[3]Unstrained values were from undeformed material in legs of bend samples.

4. Rockwell International Formability

The Rockwell International Formability report is given in its entirety in Appendix A and represents one of the most promising facets of this investigation. The material used was from the hot plus cold roll processing. In summary this report showed:

Bends	- 2.5 xt for 0.050" gage 2.7 to 3.0 xt for 0.100" gage
Joggling	- length to depth ratios were 1.9 in 90° angle specimen
Hydroforming	- for 3" part radius. Stretch flange deformation capability of 29-30%. Shrink flange capability up to 14% provided buckles which were sufficiently shallow and open to provide subsequent hand work capability.
Dimpling	- Cold dimpling with as much as 16% circumferential elongation at the dimple hole in 0.050" gage material.

5. Removal of the Air Oxidation Film from Aging

Removal of the air oxidation film from aging was investigated using several 1" wide x 6" long strips of each alloy exposed in a muffle furnace on a rack so that there was free air circulation to both sides and all edges.

One sample of each alloy was given one of the following treatments:

a) light sandblast + pickle* in 35% HNO_3-5%HF
b) pickle* hot 15% HNO_3 - 1.5%HF
c) pickle* hot 15% HNO_3 - 3%HF
d) pickle* hot 35% HNO_3 - 5%HF
e) pickle* hot 2%HF
f) KOH** bath descale + 15% HNO_3 - 1.5%HF

*Aim gage removal 0.002".
**KOH bath composition - 70-80% KOH, 15% HNO_3, balance water at 400 to 430°.

Visual examination showed that light uniform sandblasting followed by the 35 HNO_3 - 5HF bath gave the most uniform contamination removal on all three alloys with no appreciable hydrogen pickup and would be recommended as a first choice for all three alloys. The second preference was the KOH followed by the 15% HNO_3 - 1.5%HF. The Ti-8V-4Cr-2Mo-2Fe-3Al and Ti-15V-3Cr-3Al-3Sn alloys would require two complete cycles of KOH to acid for uniform scale and contamination removal, but this double KOH cycle is not unusual for titanium materials. A choice between these two methods would depend on equipment, process capability, etc., more than on alloys. The straight acid pickles all gave spotty scale removal which resulted in preferential attack and are not recommended.

B. GENERAL STUDIES

1. Foil Rolling Evaluation

The increasing use of honeycomb type materials made it desirable to examine foil capabilities for these three alloys. Beta alloys of the type represented here are excellent foil candidates because the frequency of intermediate annealing required is much lower than commercially available alpha and alpha-beta alloys.

The materials available were not sufficient to justify an attempt at rolling on a conventional foil mill so the same 4 high laboratory mill used for the lab simulated strip was used. Appropriate length panels were cut from 0.050" gage laboratory and sheet simulated strip. These were rolled directly to 0.003" gage as individual panels without intermediate annealing. Foil at 0.010 and 0.003" gages was vacuum annealed, vacuum fast cooled and flash pickled. Longitudinal and transverse tensile samples were tested which showed the following:

Alloy	Gage, In.	Test Dir.	Tensile Properties TS, Ksi	YS, Ksi	El, %
Ti-8V-7Cr-3Al-4Sn-1Zr	0.010	L	131	128	15
"	"	T	134	130	11
"	0.003	L	120	115	3
"	"	T	131	129	6
Ti-8V-4Cr-2Mo-2Fe-3Al	0.010	L	129	125	13
"	"	T	130	125	15
"	0.003	L	120	114	6
"	"	T	124	120	4
Ti-15V-3Cr-3Al-3Sn	0.010	L	121	117	16
"	"	T	122	118	16
"	0.003	L	121	116	4
"	"	T	121	119	7

Rolling capabilities and properties were comparable to Ti-8Mo-8V-2Fe-3Al alloy. Rolling of foil from conventional alpha-beta type alloys like Ti-6Al-4V requires intermediate annealing after a few per cent of cold reduction which increased the opportunity for contamination and adds to cost, making alpha-beta foil almost cost prohibitive.

2. Beta Transus Determinations

Determination of the beta to alpha beta transus of the type of alloy represented by the three under study here is difficult. One of the aims of the present program was to attempt to determine this transus at an intermediate stage of processing. In this case samples of the 3" thick sheet bar were tried but without success.

Two approaches were used:

a) Overage and then by heating at incrementally higher temperatures try to determine the temperature for disappearance of the dark structure associated with the alpha precipitate.

b) Solution treat well above the suspected transus temperature and by 16 hour heating at incrementally lower temperature determine the onset of alpha precipitation.

The same basic problems were encountered with both approaches, namely: The hot worked structure does not age uniformly and is not readily recrystallized. At the point where darkening from aging could be completely distinguished from staining or etching artifacts usually at 1150F, the material was obviously well below the transus. On heating aged material the disappearance of the aged structure was so gradual that a definite temperature could not be established.

3. Density Determinations

Densities determined for the three alloys were:

Alloy	Density Lbs./In.^{3}
Ti-8V-7Cr-3Al-4Sn-1Zr	0.173
Ti-8V-4Cr-2Mo-2Fe-3Al	0.171
Ti-15V-3Cr-3Al-3Sn	0.172

SECTION V

SUMMARY AND DISCUSSION

One of the aims of the present program was to determine if one alloy was better than the other two. The results of the present study showed:

1) All three alloys were producible by the three processes examined.

2) All three alloys had physical and mechanical properties which indicated structural potential and a superiority to present commercially available titanium alloy flat roll products in a number of potential applications. The higher density of the three alloys was offset by improved properties for most of the properties required of an aircraft structural material.

3) Formability indices indicated that all three were room temperature formable.

Recognizing then that all three alloys meet the general aims of a strip producible material with lower cost potential for application in airframes, more critical comparisons can be examined. Several approaches have been used for comparisons of this kind. One such approach to an overview is shown in Table 27, where the critical properties evaluated are rated by discrete whole numbers 1, 2, and 3 with the lower number indicating superiority to the higher. Normalizing the totals by dividing by the number of factors considered would give a ranking as shown in the last column with the Ti-8V-4Cr first choice and the Ti-15V-3Cr second. This approach has its obvious shortcomings since, for example, the large number of property tests may give a greater impact on the results than they should receive in view of the fact that all properties are considered within acceptable limits for aircraft structural materials.

Since the object of this program was to select a low cost formable titanium alloy sheet material, consider the following factor first:

TABLE 27

COMPARISON OF THE THREE ALLOYS FOR COSTS PROCESSING, PHYSICAL AND MECHANICAL PROPERTIES AND FORMABILITY

	Costs		Processing	
	Ingot + Processing	Formability Projected	Ease	Reproducibility Expected
1) Ti-8V-7Cr	1	1	2	2
2) Ti-8V-4Cr	1	1	2	2
3) Ti-15V-3Cr	2	1	1	1

Physical and Mechanical Properties

Alloy	Density	Fty + Modulus	Fcy + Modulus	Aging Capability	Fracture Toughness	da/dn	Notched Fatigue	Thermal + Dim. Stability
1	3	2	2	1	2	2	1	1
2	1	1	1	1	1	2	1	1
3	2	3	3	2	2	1	1	2

Formability

Alloy	Bend + Springback	Olsen Cup	Aging Deflection	Joggle	Dimple	Hydropress	Normalized Totals
1	2	1	1	1	1	2	1.56
2	2	1	1	1	1	2	1.28
3	1	1	1	1	1	1	1.50

Alloy	Cost	Processing	Formability	Normalized Total
Ti-8V-7Cr	2	4	8	1.4
Ti-8V-4Cr	2	4	8	1.4
Ti-15V-3Cr	3	2	6	1.1

This order of ranking of the alloys also reflects the subjective rating from the metal producer and part fabricator based on present results. The numerical ratings exaggerate the difference between the alloys but any selection involves judgment factors, some of which are discussed below.

A. COSTS

Costs are one of the most difficult parts of this study to define at the present, and to try to project these to some future date when a beta alloy would reach a production status compounds the uncertainty manyfold. The many potential uses and requirements described in the Air Force - Industry Workshop report(4) defy categorization.

A projection of costs for cold rolled and annealed flat roll product of the three alloys shows the following:

Alloy	0.050"x36"x96", 3rd Quarter 1975 Estimated Selling Price Ratio	
Ti-8V-7Cr-3Al-4Sn-1Zr	1.02	
Ti-8V-4Cr-2Mo-2Fe-3Al	1.0	(base)
Ti-15V-3Cr-3Al-3Sn	1.16	

This comparison does not take into account what is apparently the more "forgiving" nature of the Ti-15V-3Cr-3Al-3Sn alloy which would be expected to decrease the 1.16 somewhat. The mill production sequence considered in this cost comparison was:

Melt ingot
Forge slab
Condition slab
Hot roll slab to coil
Anneal, descale and pickle coil
Overall grind
Cold roll
Final anneal

The Ti-15V-3Cr-3Al-3Sn alloy could be considered more "*forgiving*" in both melting and the final anneal. In melting chromium and iron would have the greater segregation tendencies, and hence the low, 3 per cent, Cr in the Ti-15V-3Cr-3Al-3Sn alloy should give a more homogeneous ingot than for the other two alloys where Cr is 7 per cent in one and Cr 4 per cent and Fe 2 per cent in the other. The major effect expected from improved ingot homogeneity would be greater uniformity in aged properties.

At the finishing end of the production sequence the Ti-15V-3Cr-3Al-3Sn alloy was more readily recrystallized at the final anneal than the Ti-8V-7Cr-3Al-4Sn-1Zr and Ti-8V-4Cr-2Mo-2Fe-3Al alloys. This factor should also promote more uniform aged properties from the Ti-15V-3Cr-3Al-3Sn alloy.

Comparison of costs between aircraft parts formed from currently available alpha-beta titanium alloys hand mill sheet and continuously rolled strip from the three alloys involves many uncertainties, e.g., volume of usage, adaptability of product, uniformity of parts, forming procedures, cleanup of formed, heat treated parts, etc. There appears to be little doubt, however, that a continuous strip product which could be room temperature formed with a minimum restraint and cleanup after final heat treatment would offer cost reduction possibilities.

Comparison of projected beta alloy strip costs with currently available Ti-6Al-4V hand mill sheet costs for third quarter 1975 shows:

Gage, In.	Projected Price Ratio for Beta Alloy Strip to Ti-6Al-4V Sheet
0.030	1:5
0.050	1:3.5
0.070	1:3

These selling prices are based on approximately 15,000-lb quantities and are for sizes close to 36" x 96". For small quantities where continuous strip processing is not practical, beta alloy flat roll product would cost more than Ti-6Al-4V sheet alloy, of course.

B. MECHANICAL PROPERTIES

In the discussion to this point, mechanical properties of the three beta alloys have been disregarded. Actually it was somewhat surprising to see the differences obtained in the thorough examination conducted, and these should be considered where a specific application requires a particular property advantage.

1) The aged strength potential for 950°F was higher for the Ti-8V-7Cr-3Al-4Sn-1Zr alloy than for the other two alloys. The combination of 200 Ksi aged yield strength with 6 per cent elongation is of interest.

2) At the 1050°F aging temperature the Ti-8V-7Cr-3Al-4Sn-1Zr and Ti-8V-4Cr-2Mo-2Fe-3Al alloys overaged more rapidly than the Ti-15V-3Cr-3Al-3Sn. For many production cycles this would be a consideration.

3) Fracture toughness was highest for the Ti-8V-4Cr-2Mo-2Fe-3Al alloy with the other two about equal.

4) Crack growth rate, da/dn was practically unaffected by salt water or directionality for the Ti-15V-3Cr-3Al-3Sn alloy, whereas, the other two alloys had crack growth rates increased in salt water and showed directionality effects.

In these comparisons the obvious differences between alloys in the solution annealed condition must be considered.

Tensile Properties

Alloy	Test Dir.	UTS, Ksi	YS, Ksi	El, %	Min. Bend R/t Passed
Ti-8V-7Cr	L	123	119	23	---
"	T	126	125	20	3.2
Ti-8V-4Cr	L	121	119	23	---
"	T	122	118	22	2.5
Ti-15V-3Cr	L	109	106	25	---
"	T	112	109	23	2.5

Equivalent annealed conditions could not be aimed for in this study.

The question of comparison of the present alloys with commercially available beta alloys such as Ti-8Mo-8V-2Fe-3Al, Beta C, Beta III, Ti-13V-11Cr-3Al and other grades cannot be fairly answered at this point. Published property data on the commercial beta alloys is not as complete as for the present three alloys. The solution annealed and the annealed and aged tensile properties are comparable for all the beta alloys or could probably be made comparable within the flexibility of the aging treatments.

APPENDIX A

ROOM-TEMPERATURE SHEET FORMABILITY
EVALUATION OF
THREE BETA TITANIUM ALLOYS

Written by: D. L. Day

Approved by: A. Shames

Columbus Aircraft Division
Rockwell International
NR75H-162

ROOM-TEMPERATURE SHEET FORMABILITY
EVALUATION OF
THREE BETA TITANIUM ALLOYS

12 December 1975

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FORM 351-F REV 4-73

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Rockwell International

NR75H-162

ABSTRACT

As one of the final phases of evaluation of three lower-cost, formable, developmental beta titanium alloys on AFML Contract No. F33615-74-C-5063, the Columbus Aircraft Division of Rockwell International conducted a room-temperature formability study on 0.050" and 0.100" sheets from each of the three alloys for the TIMET Division of Titanium Metals Corporation of America. The evaluation consisted of bend, joggle, hydropress and hydroform, and dimpling tests under production fabrication conditions on Ti-8V-7Cr-3Al-4Sn-1Zr, Ti-8V-4Cr-2Mo-2Fe-3Al, and Ti-15V-3Cr-3Al-3Sn to establish the general level of formability and to determine, if possible, which alloy possessed the best room-temperature forming characteristics. Excellent room-temperature formability was provided by all three alloys which was considerably better than that of currently used titanium alloys, such as Ti-6Al-4V. Only minor differences were observed among the three alloys; these were the result of variations in grain size and corresponding levels of orange peel. On this basis, Ti-15V-3Cr-3Al-3Sn showed a very slight advantage with Ti-8V-7Cr-3Al-4Sn-1Zr a close second. Because of the excellent formability, this type of alloy should be considered for applications at intermediate service temperatures of 300-700F.

This study was performed as part of USAF Contract No. F33615-74-C-5063 on Rockwell Sales Order No. 2377.

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1. INTRODUCTION

Three beta titanium sheet alloys were processed by the TIMET Division of Titanium Metals Corporation of America on U. S. Air Force Contract No. F33615-74-C-5063 with the objective of developing a lower cost formable sheet material with good high-strength aged properties.[1] As a final phase of the contract, it was recommended that room-temperature formability testing be performed on the three sheet alloys to determine the forming limits for this type of new alloy and to establish, if possible, which of the three beta compositions possessed the best room-temperature formability. Subsequent discussions between TIMET, AFML, and the Columbus Aircraft Division of Rockwell International resulted in a proposal from Rockwell International to TIMET, dated 18 July 1975[2] and acceptance of the proposal by means of TIMET's Purchase Order No. 16853 of 21 August 1975.

Since it was recognized that the major potential application for this type of titanium alloy would be in aerospace, formability tests were to be related to the forming of aircraft parts. Consequently, the formability evaluation was to consist of bend, joggle, hydroform, and dimpling tests at room temperature on two sheet gages of each alloy under production fabrication conditions to determine the practical forming limits for each type of deformation and to establish, if possible, which alloy-process condition possesses the best forming characteristics. This evaluation was conducted on Rockwell Sales Order No. 2377 as part of USAF Contract No. F33615-74-C-5063.

2. TEST PROCEDURES AND RESULTS

2.1 Materials and Properties

Since one 0.050" sheet and one 0.100" sheet from each of the three alloys were to be evaluated on this program, TIMET selected material which had been hot rolled to 0.200" gage and then cold rolled and annealed to either 0.050" or 0.100". Although other processing procedures and conditions were used on other sheets, as described in a previous interim report[1], the combination of hot and cold rolling was chosen as optimum for formability testing.

Solution annealed tensile and bend properties of the six 36" x 30" sheet panels, as furnished by TIMET, are listed in Table 1. Also included are springback angles for both 45 and 135° bends. Of special note is the relatively small springback of 7-10° at an angle of 135°. The tensile properties show a spread of only 2-5 ksi between F_{tu} and F_{ty}, but at high elongation values, and transverse minimum bend radii were generally 2.5T or less. Microstructures of the six sheets are shown in Figures 1 and 2 for the 0.050" and 0.100" panels, respectively. In both thicknesses the finest-grained, more fully recrystallized structure was provided by Ti-15V-3Cr-3Al-3Sn (Heat V-5031), while the largest grain size was exhibited by Ti-8V-4Cr-2Mo-2Fe-3Al (Heat V-5030).

Upon receipt from TIMET, the six 36" x 30" sheet panels were visually examined and the thickness of each was measured around the periphery (see Table 1 for thickness ranges). Although each panel showed the remnants of surface belt grinding, the subsequent acid pickling had rounded the grind lines and left the surfaces free of any objectionable defects. No material specification covers these experimental alloys, but the sheet material did meet the flatness, surface finish, and thickness tolerance requirements of Specification Mil-T-9046.

A sketch of the layout for cutting the specimens described in reference (2) is shown in Figure 3. Originally an unused 11" x 36" piece was scheduled to be saved from each panel, but this was later utilized for additional hydropress and hydroform test specimens. During shearing and specimen preparation, operating personnel judged that the six panels in the solution annealed condition appeared to shear with somewhat greater ease than currently used titanium alloys, such as Ti-6Al-4V or Ti-6Al-2Sn-4Zr-2Mo, and were readily deburred and edge polished. Band saw cutting of the curved hydropress test specimens also seemed to be easier than Ti-6Al-4V, although no quantitative measure was made of blade wear or cutting speeds.

2.2 Bend Test Procedure and Results

The 2" x 6" bend specimens were sheared, deburred, and edge polished prior to press brake bend testing at room temperature in a 45-ton Verson Brake Press utilizing male dies of various radii in conjunction with an open channel female die. In each case, the depth of stroke of the male die was adjusted to produce a 90° bend angle after springback. Test specimens were cut to obtain bending in both directions (L and T) with respect to the sheet rolling direction; a L bend is one in which the bending force and outer-fiber tensile strain is in the longitudinal direction, while a T bend is oriented 90° from this. In general, L and T specimens from each of the six panels were bent at radii both smaller and larger than the minimum so that a satisfactory minimum bend radius (MBR) could be established. Both 2" and 6" wide bends were produced and although there was little difference between the two, the MBR was determined on the basis of 6" wide bends. During testing, it was observed that there was considerably less springback with these six sheets than is normally encountered in currently-used titanium alloys, such as Ti-6Al-4V. This corresponds with the small springback measured at 135° angles by TIMET (see Table 1).

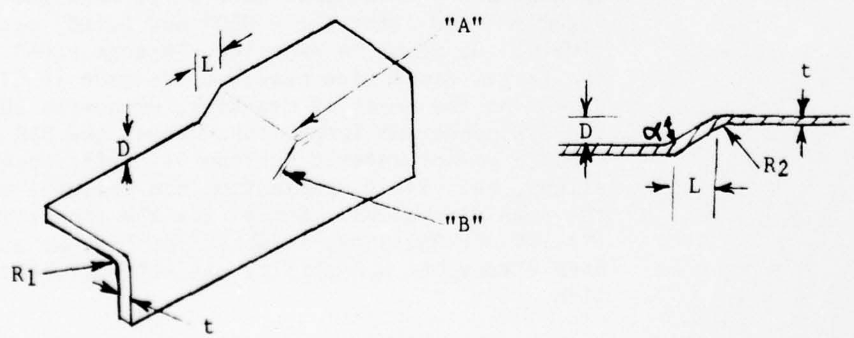
Male die radii were available in 1/32" increments and the three 0.050" sheets were tested with die radii of 3/32" to 5/32", while specimens from the three 0.100" panels were bent around dies with a radius of ¼ to 3/8". Minimum bend radii for each sheet in both directions are listed in Table 2 while photographs of bend specimens at or near the MBR are shown in Figures 4 and 5 for the 0.050" and 0.100" materials, respectively. As might be expected, "orange peel" deformation in the larger grain size panels often made it difficult to determine the onset of cracking, even with 20X magnification and dye penetrant inspection. Thus, the MBR values in Tables 4 and 5 do not reflect substantial differences among the three alloys, but visual examination did indicate some variation at the same die radius. Except for the finest grain size sheets (Ti-15V-3Cr-3Al-3Sn), in which the MBR was about the same in both directions, bendability was slightly better in the L direction.

Perhaps the most significant observation from this bend testing is the outstanding bendability provided by these beta alloys; i.e., MBR of 2.5T for the 0.050" sheets and 2.7 - 3.0 T for the 0.100" material, compared to 4.5-5.0 T for Ti-6Al-4V and Ti-6Al-2Sn-4Zr-2Mo, 4-5 T for Ti-8Mn, and 3.0-3 T for Ti-13V-11Cr-3Al. Bendability of the three alloys (two gages) is rated in descending order as follows, although the differences were not substantial*:

0.050" (2.5T)	0.100" (2.7-3.0T
Ti-15V-3Cr-3Al-3Sn	Ti-15V-3Cr-3Al-3Sn
Ti-8V-7Cr-3Al-4Sn-1Zr	Ti-8V-7Cr-3Al-4Sn-1Zr
Ti-8V-4Cr-2Mo-2Fe-3Al	Ti-8V-4Cr-2Mo-2Fe-3Al

2.3 Joggle Test Procedures and Results

Joggling is a forming process in which a portion of flat sheet or a brake formed angle part is recessed or offset to accommodate a flush connection or provide for clearance with other parts in assembly. It is produced by two parallel bends in opposite directions at the same angle as shown in the sketch below. Because the bends are close together, the same flange will contain both shrink and stretch areas in close proximity to each other. Severity of the joggle is measured by the joggle length-to-depth ratio, L/D, as illustrated below; i.e., the smaller the ratio, the more severe is the joggle[3].



* These slight differences based on variations in orange peel.

Two major failures in joggling are cracking or splitting at the upper bend transition zone ("A" in the sketch) due to excessive biaxial stresses in the "double bend" area, and buckling in the web of the transition zone ("B" in the sketch) because of excessive compression and shear deformation.

Joggling can be performed in a variety of powered presses using either fixed tooling or adjustable universal tooling in which the joggle depth (D) and the joggle length or runout (L) can be varied as required for different parts. The clip method of joggling was used for this program in which 90° V-type male and female dies were utilized in conjunction with two separate shims of varying thickness to obtain different joggle depths and spaced to provide the desired joggle length. Thus, clip joggling provided the flexibility in varying the forming parameters necessary in a test program of this type. A photograph of the tooling is shown in Figure 6.

The 2" x 6" joggle specimens (see Figure 3) were sheared, deburred, and edge polished prior to testing, and the 0.050" samples were press brake bent 90° on a 5/32" die radius (3.0-3.1T) to obtain bent angles 6" long. Orientation of the specimens was such that the bending strain was in the transverse direction. Several of the 0.100" samples were also bent 90° in a similar fashion on a 5/16" die radius (3.1T) while the remaining 0.100" test pieces were left as flat material. The 90° angle 0.050" specimens were clip joggled at room temperature starting at a joggle depth of 0.050" and a joggle length of 0.25", and increasing the joggle severity to a depth of 0.100" and a length of 0.187" (L/D = 1.9). These data are summarized in Table 3. Visual examination of the specimens indicated that this was near the joggling limit for the 0.050" sheets, although cracking or rejectable buckling was not obtained*. For this thickness, decreasing the joggle length to less than 0.187" or increasing the depth beyond 0.100" would have produced an objectionable shearing action. Joggling the 0.100" angle specimens was started at a depth of 0.100" and a length of 0.375", which produced satisfactory joggles (L/D = 3.2-3.7). However, more severe joggling deformation could not be obtained because of tooling limitations (thicker shims were not available) and the inability to decrease the joggle length without excessive shearing. A summary of these results are included in Table 3.

* Near the joggling limit based on extent of orange peel and metal deformation.

Since joggling limits could not be established on the 0.100" bent angles, flat sheet specimens (0.100" x 2" x 6") were joggled on a press brake utilizing a double channel arrangement with a 3/16" radius on the channel edges. A starting depth of about 0.100" and a length of 0.250" were increased in severity to a depth of 0.160" and a length of 0.250" (L/D = 1.56), as summarized in Table 3. At this point, pronounced "orange peel" had developed in Ti-8V-4Cr-2Mo-2Fe-3Al, to a lesser degree in Ti-8V-7Cr-3Al-4Sn-1Zr, and least in Ti-15V-3Cr-3Al-3Sn. However, actual failure had not occurred, which was confirmed by dye penetrant inspection. The extent of orange peel was directly related to the grain size of the three 0.100" sheets illustrated in Figure 2.

Photographs of the most severe joggles in both the 0.050" and 0.100" sheets are shown in Figure 7. Except for differences in orange peel (and grain size), which cannot be distinguished in the photographs, there was little difference in joggling behavior among the three alloys. However, ultimate forming limits were not reached in most cases, primarily because of the excellent joggling characteristics exhibited by these alloys and the corresponding limitations in available tooling. The L/D values for the 0.050" sheets of 1.9-2.0 compare quite favorably with 1.7 for Ti-13V-11Cr-3Al (the original beta alloy) and are considerably lower than approximately 5-6 for Ti-6Al-4V and Ti-6Al-2Sn-4Zr-2Mo joggled at room temperature.

2.4 Hydropress - Hydroform Test Procedures and Results

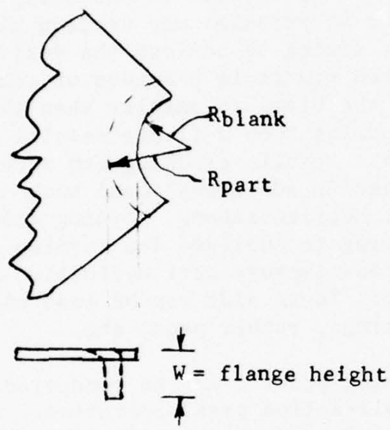
The hydropress or trapped rubber forming process relies entirely on the flow of rubber in a confined area to transmit the press ram force to the piece being formed. This rubber pad normally serves as the female die and acts as a fluid to force the sheet metal around the male die or form block. Use of this process offers the advantages of less costly tooling and the ability to form several small parts at one time. It is utilized principally for flanging and for shallow recessed parts, and is suitable for forming straight bends, channel sections, curved flanges, beads, ribs, offsets, contours, and other similar features on predominantly flat sheet metal parts. A sketch of the hydropress rubber forming process is shown in Figure 8.

A shrink flange is a curved or convex flange in which the radius of the blank is greater than the final radius of the part. Forming such a flange results in shrinking the material and as a result, buckles or wrinkles may develop which require additional hand work or sizing to achieve the desired part configuration. A stretch flange is a curved or concave flange in which the radius of the blank is smaller than the final radius of the part. Forming such a flange results in stretching the material and as a result, cracking can occur or incomplete forming may require additional hand work or sizing to obtain the desired part configuration. Forming aids are often used in hydropress forming to increase the forming pressure in critical areas and thus improve part definition and reduce subsequent hand forming. These aids can be lead wipers, wedge blocks, drawing rings, rubber pads, etc.

The trapped rubber forming process may be conducted either as a single-action or double-action press operation. Single action is a straight hydropress procedure shown in Figure 8 in which the male tool and blank are supported on a stationary bottom press platen and the trapped-rubber head is lowered over the blank and tool with application of pressure(3). All of the smaller specimens and a few of the larger ones in this program were formed in this manner. In the double-action process (tooling is illustrated at the right side of Figure 9), the blank is clamped to the support plate by the rubber pad and then the punch from the bottom is forced against the blank which is formed into the rubber pad. With the edges of the flanges "clamped" by the rubber and an increase in rubber pad pressure, there is a drawing action which tends to reduce buckles and wrinkles in the shrink flange. This procedure has been termed drawforming or hydroforming and was used on several larger specimens in this program.

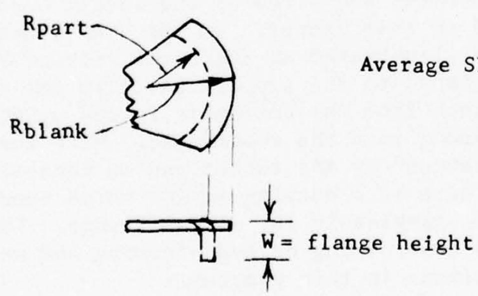
For the initial hydropress testing in this program, specimens were cut for a small 3" tool radius with shrink flanges of various heights to obtain several levels of shrink. Height of the stretch flange was cut to represent a high degree of stretch with plans for trimming the flange height as required after the initial tests were completed. Tooling is shown in Figure 10. Sample blanks were cut on a band saw, deburred, and the edges polished. Calculations for the level of stretch and shrink are based on the radius of the blank and tool or part radius (either 3" or 8" for this program), which involves the flange height, and are shown as follows:

Stretch Flange



Average Stretch, % = $\frac{R_{part} - R_{blank}}{R_{blank}}$ X 100

Shrink Flange



Average Shrink, % $\frac{R_{blank} - R_{part}}{R_{blank}}$ X 100

Following completion of hydropress tests on 3" radius specimens, the remainder of the 11" x 36" piece of material from four of the six original sheets (see Figure 3) was utilized for 8" radius specimens, most of which were draw formed. Although these larger specimens were not part of the original evaluation, the additional testing was considered important in the overall assessment of the formability of the three alloys.

Testing procedures for the straight hydropress specimens were essentially the same as outlined previously in this section. A 2700-ton Cincinnati Hydroform Press was used with a 25" diameter rubber trap and a maximum forming pressure of 10,000 psi. A photograph of this press is shown in Figure 11. A pressure of 6,000 psi was used for the 0.050" specimens with a 3" tool radius; this was increased to 10,000 psi for the 0.100" samples and for each of the larger specimens (8" tool radius) which were subjected to straight hydropress forming. A maximum pressure of 6,000 psi was used on the larger draw formed samples; this upper limit was established because permanent deflection of the unsupported flat plate tooling on the lower platen did not permit higher pressures to be utilized.

Results of hydropress forming the specimens with a 3" tool radius are summarized in Table 4 which covers shrink levels from 7 to 25 percent and stretch levels from 26 to about 29-30 percent. Photographs of most of the 0.050" test pieces are shown in Figure 12 and 13 (convex and concave sides, respectively). The stretch flange capability of all three alloys at 0.050" gage was outstanding in that each was stretched 29-30 percent without failure. Only one stretch flange failed (by splitting) and this was by positioning the blank on the die to achieve about 50 percent stretch. The fact that the 29-30 percent stretch flange capability exceeds the tensile elongation values of 21-24 percent (see Table 1) is attributed to the restraint by the rubber pad with a different stress state during forming than is present in a tensile specimen. Severe buckles were obtained in the shrink flanges at 20 per cent shrink or greater. At 7-14 percent shrink the buckles were more shallow and open, such that they could be hand worked to achieve the desired configuration. A shrink level of 17 percent appears to be marginal regarding the ability to hand work the flange. No significant differences were observed among the three alloys other than variations in the degree of "orange peel" discussed previously.

Improvement in the shape of the shrink flange of 0.050" material by using a lead forming aid (shrink flange arc with 3" radius to wipe down the flange during forming) is shown at the lower left of Figure 14. As can be seen, the buckles and wrinkles are shallower and more numerous than the severe buckles obtained without a forming aid, each at a shrink level of 25 percent, and could be removed by hand working. Thus, the advantages of using forming aids is obvious. Incomplete forming of flanges

in 0.100" thick specimens (26 percent stretch and 25 percent shrink) is illustrated on the right side of Figure 14, even at maximum pressure of 10,000 psi. Although the material has the capability to be formed more completely than was achieved, the short flanges combined with the relatively small specimen blanks did not provide sufficient area for effective application of forming forces.

Testing of large specimens (8" tool radius with a 0.250" radius at the edges of the die) was conducted on the 11" x 36" pieces (Figure 3) from the three 0.050" sheets and one of the 0.100" panels (Ti-15V-3Cr-3Al-3Sn). Duplicate specimens were cut at each of two flange heights, 1.0" and 1.5", which are equivalent to the following average levels of stretch and shrink:

Flange Height	Stretch, %	Shrink, %
1.0"	14.3	11.1
1.5"	23.1	15.8

It should be noted that after band saw cutting, edges of the blanks were deburred but were not polished, since observations during the course of the program indicated a lack of sensitivity to edge discontinuities by the three alloys.

Of the 16 specimens in this phase, 13 were draw formed at room temperature on the 2700-ton Cincinnati Hydroform equipment (Figures 9 and 11) with a summary of the results listed in Table 5. The last three sample blanks (one 0.050" and two 0.100" with flange height of 1.5") were formed with the same male die, but in a straight hydropress operation. Seven of these specimens are depicted in the photographs of Figures 15 and 16 showing the convex and concave sides, respectively. Even at 15 percent shrink, the advantages of draw forming were quite pronounced. As seen in Figure 16, the shrink flanges of both the 0.050" and 0.100" specimens possessed minor buckles or wrinkles which could be removed by hand working, while the severe buckles in the 0.050" sample formed by straight hydropress are obvious (lower right corner of Figure 16). Stretch flanges (23%) in the 0.050" sheet exhibited considerable springback except in the middle of the flanges (Figure 16). Much better stretch flange definition was achieved in the draw formed 0.100" specimens, especially in the shorter 1.0" flange (14% stretch). Incomplete forming of the shrink flange with some buckling was observed in the straight hydropress formed 0.100" test piece, as shown in Figure 16. Two of the 0.050" draw formed specimens were re-run in a hydropress

operation to determine if the wrinkles could be smoothed out and the springback in the stretch flange could be reduced. However, no significant improvements were obtained, no doubt because of the prior work hardening from draw forming.

Testing of the larger 8" radius specimens showed that draw forming produced only minor buckling or wrinkling in the 15 percent shrink flanges, but resulted in some springback in the stretch flanges of the 0.050" material. It also showed that with the larger specimens and longer flanges, the 0.100" sheet could be satisfactorily draw formed with much less springback in the stretch flange than exhibited by the 0.050" material. In both gages, draw forming provided much better part definition than hydropress forming. As with joggling, hydropress and draw forming showed essentially no differences among the three alloys, although the room temperature formability of each was substantially better than currently-used alpha or alpha-beta titanium alloys or the original beta alloy shown below:

Maximum Hydropress Forming Criteria*

Alloy**	Stretch, %	Shrink, %
Formable Beta Alloys (current program)	25	14
Ti-6Al-4V	5	4
Ti-8Mn	10	5
Ti 13V-11Cr-3Al	12	8

* Rockwell-CAD manufacturing limits.
** For material thickness through 0.070-0.080"

2.5 Dimpling Test Procedure and Results

Dimpling is a forming process in which a small recessed conical flange is produced around a hole to accommodate flush-headed fasteners. It is usually applied to sheet material that is too thin for countersinking. Sheets are almost always dimpled in the condition they are to be used, since subsequent heat treatment could cause distortion and misalignment of the holes. Also, titanium alloys are normally dimpled at elevated temperatures with heated dies or by means of resistance heating to reduce forming pressures, springback, and the chances for cracking(3).

Ram coin-dimpling is the most common process in which pressure in excess of that required for forming the conical flange is applied to coin the dimpled area and reduce the amount of springback. Preparation for dimpling consists of drilling a pilot hole with a stub drill of a size applicable to aluminum alloys and deburring with a deburring tool or countersink cutter only to remove the material turned up by the drill at the edges of the hole. Coin-dimpling tools consist of a punch pilot attached to the end of the male conical die with a matched female counterpart. In dimpling, the punch pilot is positioned in the pilot hole for proper alignment and the die assembly is clamped to the sheet. Then the major forming of the recessed flange is conducted, followed by maximum pressure to coin the flange and obtain any circumferential deformation in the hole.

In this program, duplicate 4" x 6" panels were sheared from each of the six sheets (see layout in Figure 3) and on 1" centers, six rows of pilot holes (4 replicates in each row) were drilled for dimpling. The first three rows were for AN-426 rivet dimples (1/8", 5/32", and 3/16") and the last three rows were for AN-509 screw dimples (for threaded fasteners) with No. 8, No. 10 and 1/4" fasteners, all with 100° fastener heads. Pilot hole sizes are included in the data listed in Table 6. Manufacturing personnel noted that drilling of these pilot holes appeared to be more difficult than in Ti-6Al-4V. For example, three high-speed drills were used in drilling 24 - 1/8" diameter holes in the 0.100" gage, because of tool wear.

Dimpling was performed in a 20,000 pound capacity C-frame CP450EA machine manufactured by Chicago Penumatic Tool Company. Although all the dimpling was done at room temperature, this machine is also equipped for hot dimpling. The 0.050" material was dimpled first without any apparent difficulty and then, surprisingly, the 0.100" sheet also dimpled satisfactorily with only slightly higher forming pressures than for 0.050". Near maximum force from the dimpling machine was required for all but the AN-426-4 and -5 rivet dimples, which required about 60 percent of capacity. AN-426-4 (1/8") rivet dimpling was attempted in the 0.100" sheet, but because of severe seizing to the punch pilot, only three such dimples were formed, as shown in Figure 17 in the upper row on the 0.100" Ti-8V-7Cr-3Al-4Sn-1Zr (lower left panel). Photographs of the dimples in the six sheets are also shown in Figure 17.

It should be noted that the dimple sizes selected covered a desirable range of design loads for matching the fastener sizes with sheet thickness for the 0.050" gage, but the smaller dimple sizes were a decided mismatch for the 0.100" material. Thus, from a practical design standpoint, all three alloys dimpled quite satisfactorily at room temperature in the solution annealed condition (sheet thicker than about 0.070" is normally not dimpled; 0.100" material would be countersunk).

Hole sizes were measured after dimpling and these data are included in Table 6. Comparison of the dimple hole diameters with those of the starting pilot holes showed that as much as 16 percent circumferential elongation was obtained in the AN-509-1/4" dimple in the 0.050" sheets. However, all of the dimpled holes in the 0.100" panels were slightly smaller than the starting pilot holes indicating that there was insufficient forming force available to achieve circumferential deformation in the thicker material.

As stated earlier in this section, titanium alloys of necessity are nearly always dimpled at elevated temperatures. Therefore, the fact that these three beta alloys, even at a thickness of 0.100", were satisfactorily dimpled at room temperature is additional confirmation of their excellent formability. The only difference among the three was the somewhat more pronouced orange peel at the shoulder bend radius of the dimples in Ti-8V-4Cr-2Mo-2Fe-3Al.

3. SUMMARY AND CONCLUSIONS

As one of the final phases of evaluation of three lower-cost, formable, developmental beta titanium alloys on AFML Contract No. F33615-74-C-5063, the TIMET Division of the Titanium Metals Corporation of America contracted with the Columbus Aircraft Division (CAD) of Rockwell International for CAD to conduct room-temperature formability tests on solution annealed 0.050" and 0.100" sheets from each of the three alloys to establish the general level of formability and forming limits for this more-ductile type of titanium sheet material and to determine, if possible, which of the three alloys possessed the best room-temperature forming characteristics. The three alloy compositions are as follows:

Ti-8V-7Cr-3Al-4Sn-1Zr
Ti-8V-4Cr-2Mo-2Fe-3Al
Ti-15V-3Cr-3Al-3Sn

Formability tests at room temperature under production fabrication conditions consisted of:

1. Bend tests (both longitudinal and transverse, 2" and 6" wide).

2. Joggle tests.

3. Hydropress and hydroform (shrink and stretch flanges).

4. Dimpling tests.

In comparison with forming of Ti-6Al-4V and other currently used titanium alloys, the following observations and conclusions were made:

Shearing and Cutting

Compared to Ti-6Al-4V, the three alloys appeared to shear and cut by band sawing with somewhat greater ease. Deburring and edge polishing were readily accomplished. However, in drilling pilot holes in the 0.100" sheets for dimpling, greater tool wear was observed.

Bending

1. Excellent room-temperature bendability was provided by all three alloys in both gages. Minimum bend radius (MBR) was 2.5T for the 0.050" sheets and 2.7-3.0T for the 0.100" materials, compared to 4.5-5.0T for Ti-6Al-4V, 4-5T for Ti-8Mn, and 3.0-3.5T for Ti-13V-11Cr-3Al (also a beta alloy).

2. Although there was little difference in bendability among the three alloys, the finest-grained material, Ti-15V-3Cr-3Al-3Sn, was rated the best and the coarest-grained sheet, Ti-8V-4Cr-2Mo-2Fe-3Al, was judged the least attractive because of its "orange peel" deformed surfaces. Except for the finest grain size sheets of Ti-15V-3Cr-3Al-3Sn, in which bendability was about the same in both directions, MBR was slightly better in the longitudinal than in the transverse direction.

3. Springback after bending was significantly less than for Ti-6Al-4V.

Joggling

1. Because of limitations in the size of available tooling components, which prevented use of the most severe joggling parameters, the ultimate joggle forming limits were not established for the six sheets. However, all demonstrated extremely good room-temperature joggling characteristics substantially better than currently-used titanium alloys. The only significant differences among the three alloys were the variations in orange peel which relate to grain size, i.e., Ti-15V-3Cr-3Al-3Sn exhibited the least orange peel and Ti-8V-4Cr-2Mo-2Fe-3Al displayed the most.

2. A joggle length-to-depth ratio, L/D (the smaller the ratio the more severe the joggle) of 1.9 was obtained in 90° angle specimens of the 0.050" sheets compared to much larger L/D values of 5-6 commonly used as manufacturing criteria for Ti-6Al-4V and Ti-6Al-2Sn-4Zr-2Mo sheet joggled at room temperature.

Hydroforming

1. Hydropress forming of smaller 3" part radius 0.050" specimens at room temperature resulted in exceptional stretch-flange deformation capability of 29-30 percent stretch without any failure. Shrink flanges were limited to about 14 percent shrink to provide buckles which were sufficiently shallow and open that the desired configuration could have been obtained by subsequent hand working. These levels are considerably higher than the 5-10 percent stretch and 4-5 percent shrink permitted for Ti-6Al-4V and Ti-8Mn. Limited use of lead forming aids on a 25 percent shrink flange showed that this is a promising technique for reducing the buckling severity at high shrink values). Hydropress forming attempts on thicker 0.100" material (3" part radius) resulted in incomplete forming.

2. Limited hydropress forming of larger pieces (8" part radius) provided good stretch flange definition (23 percent stretch) in both thicknesses, but rather severe buckles in the 15 percent shrink flange of 0.050" material and somewhat open buckles in the 0.100" sheet.

Draw forming in the hydroform process produced only minor wrinkles in the 15 percent shrink flange, but springback at the ends of the stretch flange was obtained which was most pronounced in the longer 23 percent flange in the thinner 0.050" material. Thus, in both gages, draw forming provided much better over-all forming and part definition than straight hydropress forming.

3. Essentially no differences were observed among the three alloys during hydropress or draw forming other than the degree of orange peel in highly deformed areas, which is related to grain size variations. These materials were not sensitive to edge discontinuities as shown by the ability to deform in the presence of a saw cut interruption at the edge of a few stretch flanges without any failure, even though these edges had only been deburred without any edge polishing.

Dimpling

Although titanium alloys are almost always dimpled at elevated temperatures and normally in thicknesses less than 0.070-0.080", it was demonstrated that all three alloys in both gages could be satisfactorily dimpled at room temperature for both rivet (1/8 to 3/16" diameter) and threaded fasteners (No. 8 to 1/4" diameter) covering the range of practical matching design between fastener and sheet sizes. This represented as much as 16 percent circumferential elongation at the dimple hole in e 0.050" material. The only difference among the three alloys was the somewhat greater evidence of orange peel at shoulders of the dimples in Ti-8V-4Cr-2Mo-2Fe-3Al.

This formability test program showed that the three beta alloys in the solution annealed condition possessed excellent room-temperature forming characteristics. Only minor differences in formability were observed among the three alloys; these appeared to be the result of variations in recrystallized (partial or complete) grain size and corresponding degree of orange peel. On this basis, Ti-15V-3Cr-3Al-3Sn provided the least orange peel with Ti-8V-7Cr-3Al-4Sn-1Zr a close second. It may be that with equivalent grain size, even this minor difference among the three compositions would have disappeared.

Although Ti-15V-3Cr-3Al-3Sn provided very slightly better formability, such other considerations as differences in ingot cost, processing, recrystallization and aging behavior, and higher-strength aged properties may dictate that one of the other alloys is optimum. Regardless, the outstanding room-temperature forming behavior of this type of beta titanium alloy shows that it should be considered for use in the intermediate temperature range of 300-700F.

ACKNOWLEDGEMENT

The very helpful recommendations made and assistance offered in the planning and conducting of this program by L. Odor and S. T. Lazaroff, as well as Manufacturing personnel, in the Columbus Aircraft Division of Rockwell International are gratefully acknowledged.

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TABLE 1

ROOM-TEMPERATURE TENSILE AND BEND PROPERTIES OF SOLUTION ANNEALED FORMABLE BETA TITANIUM SHEET ALLOYS*

Heat No.	Alloy	Test Dir.	Tensile Properties Ftu Ksi	Fty Ksi	Elong. %	Bend Min. R/t, Passed at 20X	Springback, ° for Bend Angle, ° 45	135
	0.050-In. Gage Sheet							
V-5029-07	Ti-8V-7Cr-3Al-4Sn-1Zr	L	127	123	21	---	21	7
(0.050/0.051")	(Annealed 1400F-10 Min.)	T	129	126	21	2.0	25	7
V-5030-07	Ti-8V-4Cr-2Mo-2Fe-3Al	L	121	117	24	---	22	8
(0.0515/0.053")	(Annealed 1500F-10 Min.)	T	123	119	21	2.1	23	8
V-5031-07	Ti-15V-3Cr-3Al-3Sn	L	111	107	24	---	22	8
(0.050/0.052")	(Annealed 1450F-10 min.)	T	113	109	23	2.1	22	7
	0.100-In. Gage Sheet							
V-5029-06	Ti-8V-7Cr-3Al-4Sn-1Zr	L	121	119	23	---	26	10
(0.100"/0.104")	(Annealed 1400F-10 Min.)	T	123	119	22	2.5	25	11
V-5030-06	Ti-8V-4Cr-2Mo-2Fe-3Al	L	124	119	19	---	23	10
(0.093/0.099")	(Annealed 1500F-10 Min.)	T	128	124	17	3.2	23	9
V-5031-06	Ti-15V-3Cr-3Al-3Sn	L	110	106	24	---	23	9
(0.102/0.104')	(Annealed 1450F-10 min.)	T	112	109	24	2.5	22	10

* Except for gage measurements shown with heat number, data supplied by TIMET.

TABLE 2

MINIMUM PRESS BRAKE BEND RADII
FOR 0.050" AND 0.100" BETA TITANIUM ALLOY SHEETS *

Alloy	Nominal Gage, In.	Test Dir.(1)	Die Radius, In.	MBR(R/t), T(2)
Ti-8V-7Cr-3Al-4Sn-1Zr	0.050	L	1/8	2.5
Ti-8V-7Cr-3Al-4Sn-1Zr	0.050	T	1/8	2.5
Ti-8V-7Cr-3Al-4Sn-1Zr	0.100	L	9/32	2.8
Ti-8V-7Cr-3Al-4Sn-1Zr	0.100	T	5/16	3.1
Ti-8V-4Cr-2Mo-2Fe-3Al	0.050	L	1/8	2.4(3)
Ti-8V-4Cr-2Mo-2Fe-3Al	0.050	T	1/8	2.4(3)
Ti-8V-4Cr-2Mo-2Fe-3Al	0.100	L	9/32	2.9(3)
Ti-8V-4Cr-2Mo-2Fe-3Al	0.100	T	9/32	2.9(3)
Ti-15V-3Cr-3Al-3Sn	0.050	L	1/8	2.5
Ti-15V-3Cr-3Al-3Sn	0.050	T	1/8	2.5
Ti-15V-3Cr-3Al-3Sn	0.100	L	9/32	2.7
Ti-15V-3Cr-3Al-3Sn	0.100	T	9/32	2.7

(1) Bending strain in relation to rolling direction.

(2) Minimum bend radius, T (die radius/sheet thickness), as determined by 20X magnification and dye penetrant inspection.

(3) Severe orange peel, but apparently no surface openings.

* Based on 54 bend tests.

TABLE 3

SUMMARY OF DATA FROM MOST SEVERE ROOM-TEMPERATURE JOGGLING OF 0.050" AND 0.100" BETA TITANIUM ALLOY SHEETS*

Alloy	Gage, In.	Joggle Depth, In.	Joggle Length, In.	L/D(1)
Ti-8V-7Cr-3Al-4Sn-1Zr	0.050	0.090	0.187	2.0(2)
Ti-8V-7Cr-3Al-4Sn-1Zr	0.100	0.114	0.375	3.2(3)
Ti-8V-7Cr-3Al-4Sn-1Zr	0.100	0.160	0.250	1.56(4)
Ti-8V-4Cr-2Mo-2Fe-3Al	0.050	0.100	0.187	1.9(2)
Ti-8V-4Cr-2Mo-2Fe-3Al	0.100	0.100	0.375	3.7(3)
Ti-8V-4Cr-2Mo-2Fe-3Al	0.100	0.160	0.250	1.56(4)
Ti-15V-3Cr-3Al-3Sn	0.050	0.100	0.187	1.9(2)
Ti-15V-3Cr-3Al-3Sn	0.100	0.103	0.375	3.7(3)
Ti-15V-3Cr-3Al-3Sn	0.100	0.160	0.250	1.56(4)

(1) L/D is ratio of joggle length to joggle depth; the lower this ratio the more severe the joggle.

(2) Bent 90° at 3.0T radius prior to joggling. Value represents near the limit in joggling deformation and tooling capability.

(3) Bent 90° at 3.1T radius prior to joggling. Value does not represent limit in joggling deformation capability, but was the most severe L/D ratio obtained with available tooling.

(4) Joggles on flat 2" x 6" specimens. Value is near the limit for joggling this 0.100" material.

* Data based on 33 joggle tests.

TABLE 4

SUMMARY OF ROOM-TEMPERATURE HYDROPRESS FORMING OF 3" RADIUS SHRINK AND STRETCH FLANGES IN 0.050" AND 0.100" BETA TITANIUM ALLOY SHEETS (1)

Hydroform Pressure, psi(2)	Stretch Flange, %(3)	Shrink Flange %	Shrink Flange Remarks
0.050"			
6,000	26	7.7	4 or 5 very shallow buckles
6,000	26	11	5 very shallow buckles
6,000	26	14	4 or 5 shallow buckles
6,000	26	17	4 relatively open buckles
6,000	26	20	3 or 4 pinched buckles
6,000	26	22.5	3 or 4 tightly pinched buckles
6,000	26	25	3 tightly pinched buckles
6,000	30	25	4 tightly pinched buckles
6,000	50(4)	25	4 tightly pinched buckles
10,000	26	25	3 tightly pinched and cracked buckles
10,000	26	25	Lead forming aid used; 6 relatively open buckles
0.100" Sheet from the Three Alloys			
10,000	26	25	Only partial forming with both flanges 30-45° instead of 90°
10,000	26	25	Stretch flange formed only 30°; 2 buckles in shrink flange

(1) All three alloys at 0.050" hydropress formed in nearly identical fashion; remarks apply to all 0.050" material. Total of 33 tests.

(2) Forming conducted in 2700-ton Cincinnati Hydroform press with 25" diameter ram and maximum forming pressure of 10,000 psi. Radius on edges of die for 0.050" was 5/32" and for 0.100" the radius was 5/16".

(3) All 26 and 30% stretch flanges exhibited no evidence of cracking and conformed to the die with little or no springback.

(4) Sample blank of 0.050" Ti-15V-3Cr-3Al-3Sn deliberately shifted on die to achieve higher level of stretch. After forming, flange height was equivalent to 50% stretch and flange had completely split open.

TABLE 5

SUMMARY OF ROOM-TEMPERATURE DRAW FORMING (HYDROFORM) AND LIMITED HYDROPRESS FORMING OF 8" RADIUS SHRINK AND STRETCH FLANGES IN 0.050" AND 0.100" BETA TITANIUM ALLOY SHEETS(1)

Initial Clamping Pressure, psi	Major Forming Pressure, psi	Final Draw Form Pressure, psi	Stretch Flange, %	Shrink Flange, %	Remarks
		Draw Forming			
0.050"					
2000	3000	4000	14	11	No cracks. Good stretch flange definition; 7 shallow buckles in shrink flange
3000	4500	5500	14	11	No cracks. Good stretch flange definition; less wrinkles in stretch flange than at lower pressures.
3000	4500	5500	23	15	No cracks. Pronounced springback both ends of stretch flange; shallow wrinkles in shrink flange.
3500	5000	6000	23	15	No cracks. Pronounced springback both ends of stretch flange; shallow wrinkles in shrink flange.
0.100"(2)					
3500	5000	6000	14	11	No cracks; good part definition with minor springback in stretch flange and shallow wrinkles in shrink flange.
3500	5000	6000	23	15	No cracks. Slightly greater springback than at 14% stretch; more shallow wrinkles than in 11% shrink flange.
		Straight Hydropress			
0.050"(2)	10,000	--	23	15	No cracks; good stretch flange definition (minor springback) and 4 tightly pinched buckles in shrink flange.
0.100"(2)	10,000	--	14	11	No cracks; good stretch flange definition (minor springback) and incomplete forming of shrink flange.
0.100"(2)	10,000	--	23	15	No cracks; good stretch flange definition (minor springback). Complete forming of shrink flange but 2 rather severe buckles.

(1) All three alloys at 0.050" draw formed in nearly identical fashion; remarks apply to all 0.050" material. Radius at edges of male die = 1/4". Specimen blank edges deburred but not polished prior to forming.

(2) Ti-15V-3Cr-3Al-3Sn

TABLE 6

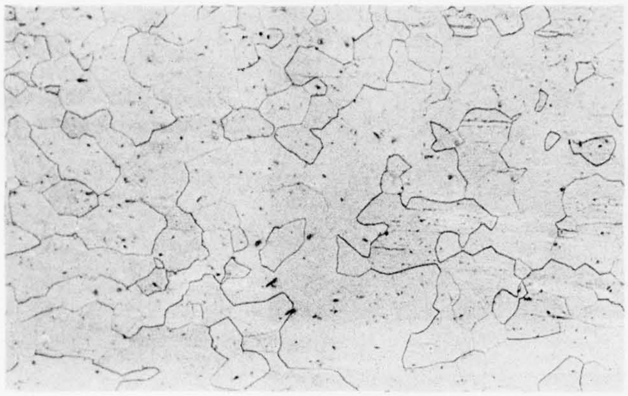
SUMMARY OF DATA FROM ROOM-TEMPERATURE DIMPLING OF 0.050" AND 0.100" BETA TITANIUM ALLOY SHEETS(1)

Dimpling Die, Type and Size	Drilled Pilot Hole Size and Dia., In.	Nominal Sheet Gage, In.	Dimpled Hole Dia., In.	Circumferential Elongation at Dimpled Hole, %(2)
Screw Dimples				
AN-509-1/4"(3)	#5 (0.2055)	0.050	0.238	16.0
AN-509-1/4"(3)	#5 (0.2055)	0.100	0.203	--
AN-509 #10	#24 (0.152)	0.050	0.169	11.2
AN-509 #10	#24 (0.152)	0.100	0.144	--
AN-509 #8(3)	#29 (0.136)	0.050	0.149	9.6
AN-509 #8(3)	#29 (0.136)	0.100	0.128	--
Rivet Dimples				
AN-426-6(3)	#11 (0.191)	0.050	0.201	5.3
AN-426-6(3)	#11 (0.191)	0.100	0.189	--
AN-426-5	#21 (0.159)	0.050	0.161	1.3
AN-426-5	#21 (0.159)	0.100	0.157	--
AN-426-4	0.125	0.050	0.128	2.4
AN-426-4	0.125	0.100	--	--

(1) Within each gage, the three alloys dimpled in nearly identical fashion; data apply to all three alloys. Dimpling performed in 20,000 pound capacity CP450EA Chicago Pneumatic Machine.

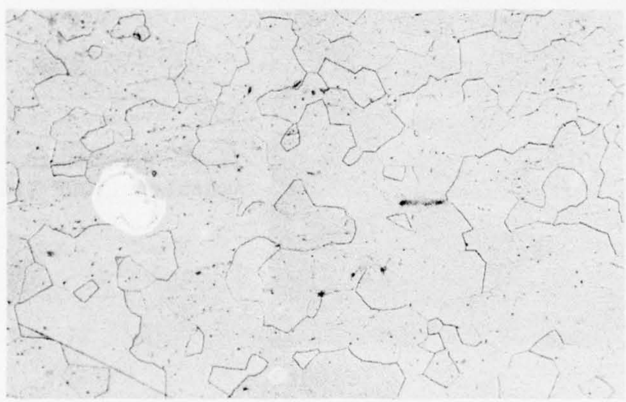
(2) Dimpled hole diameters in 0.100" sheets were somewhat smaller than pilot hole diameters; therefore, no elongation at the hole was obtained during dimpling.

(3) Near maximum dimpling machine pressure required for both sheet thicknesses.



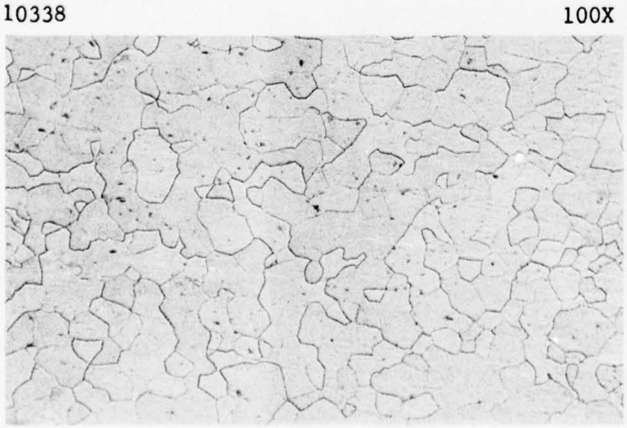
10337 100X

Ti-8V-7Cr-3Al-4Sn-1Zr
Annealed 1400F (10 Min.)



10338 100X

Ti-8V-4Cr-2Mo-2Fe-3Al
Annealed 1500F (10 Min.)



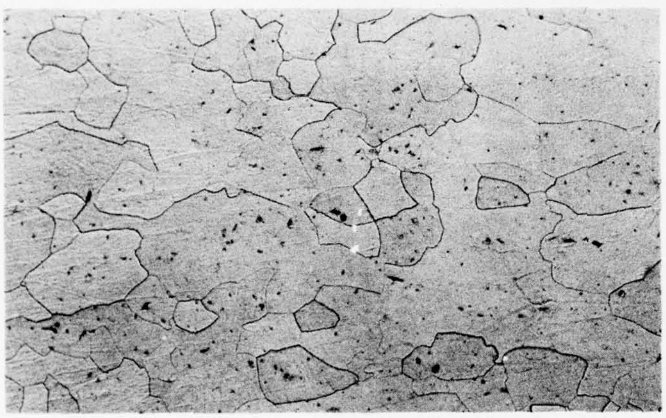
10340 100X

Ti-15V-3Cr-3Al-3Sn
Annealed 1450F (10 Min.)

FIGURE 1. AS-RECEIVED SOLUTION ANNEALED MICROSTRUCTURES OF THE THREE 0.050" SHEETS SHOWING REPRESENTATIVE GRAIN SIZE (LONGITUDINAL SECTIONS).

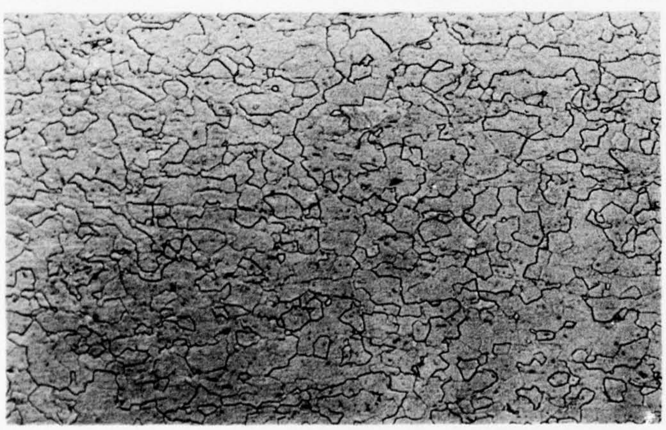
10339 100X

Ti-8V-7Cr-3Al-4Sn-1Zr
Annealed 1400F (10 Min.)



10341 100X

Ti-8V-4Cr-2Mo-2Fe-3Al
Annealed 1500F (10 Min.)



10336 100X

Ti-15V-3Cr-3Al-3Sn
Annealed 1450F (10 Min.)

FIGURE 2. AS-RECEIVED SOLUTION ANNEALED MICROSTRUCTURES OF THE THREE 0.100" SHEETS SHOWING REPRESENTATIVE GRAIN SIZE (LONGITUDINAL SECTIONS).

B - BEND SPECIMENS
J - JOGGLE SPECIMENS
D - DIMPLE PANELS
H - HYDROPRESS (3" tool radius)

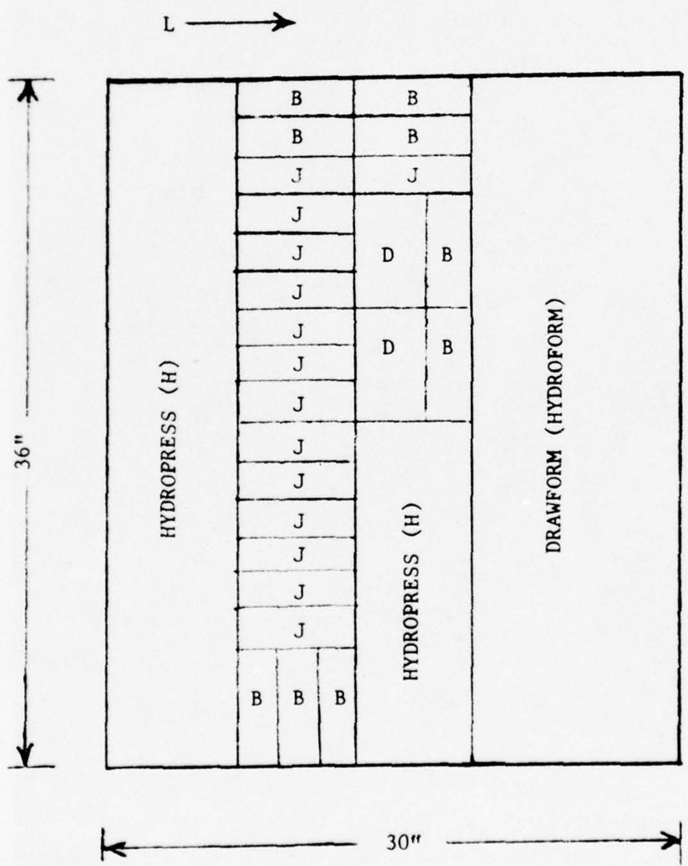
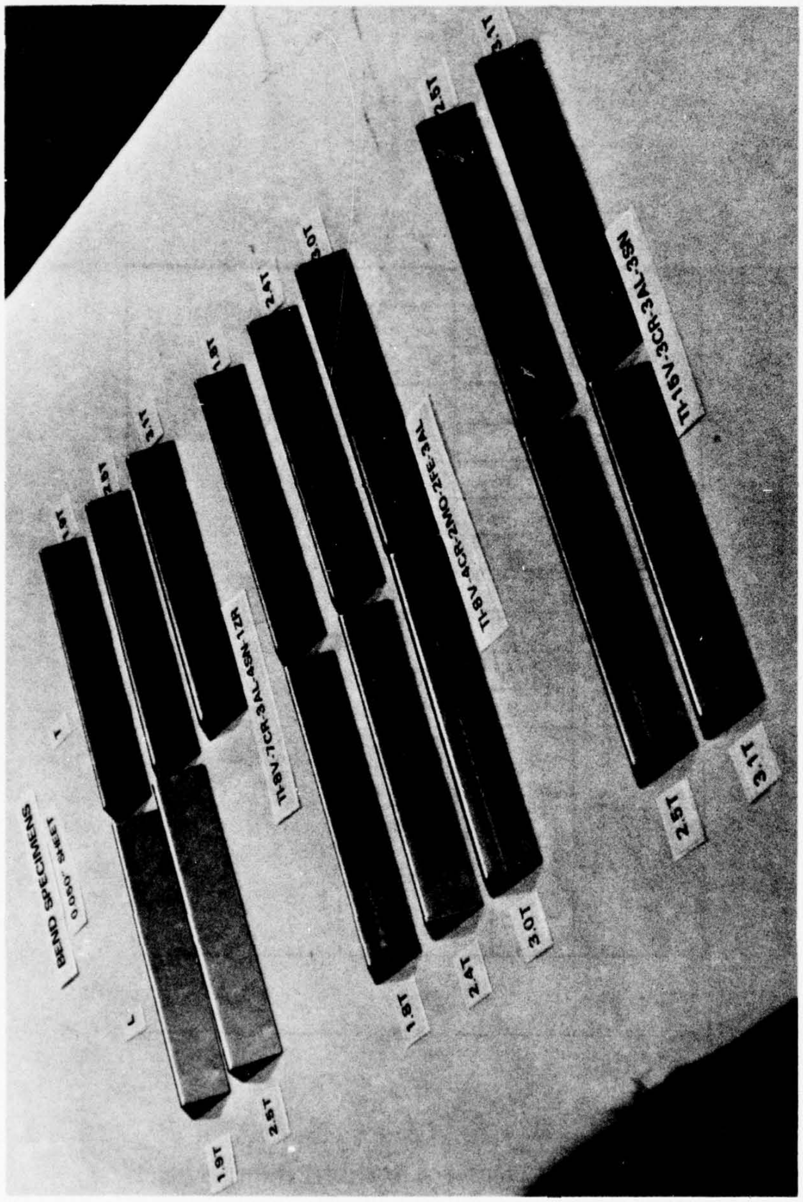
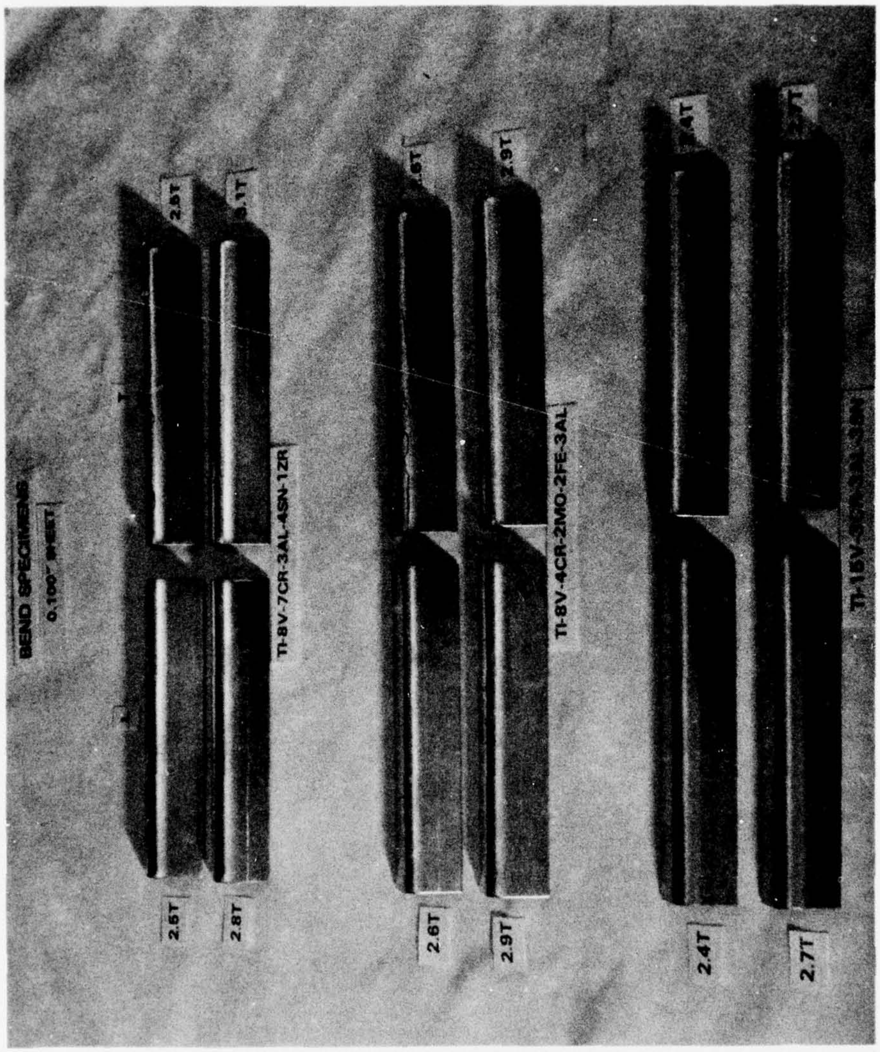


FIGURE 3. SPECIMEN LAYOUT FOR FORMABILITY TESTING OF 0.050" AND 0.100" SHEETS



10302

FIGURE 4. BEND SPECIMENS (0.050" GAGE X 6" WIDTH) OF THE THREE BETA TITANIUM ALLOYS IN THE RANGE OF THE MINIMUM BEND RADIUS (T = R/t)



10303

FIGURE 5. BEND SPECIMENS (0.100" GAGE x 6" WIDTH) OF THE THREE BETA TITANIUM ALLOYS IN THE RANGE OF THE MINIMUM BEND RADIUS (T = R/t)

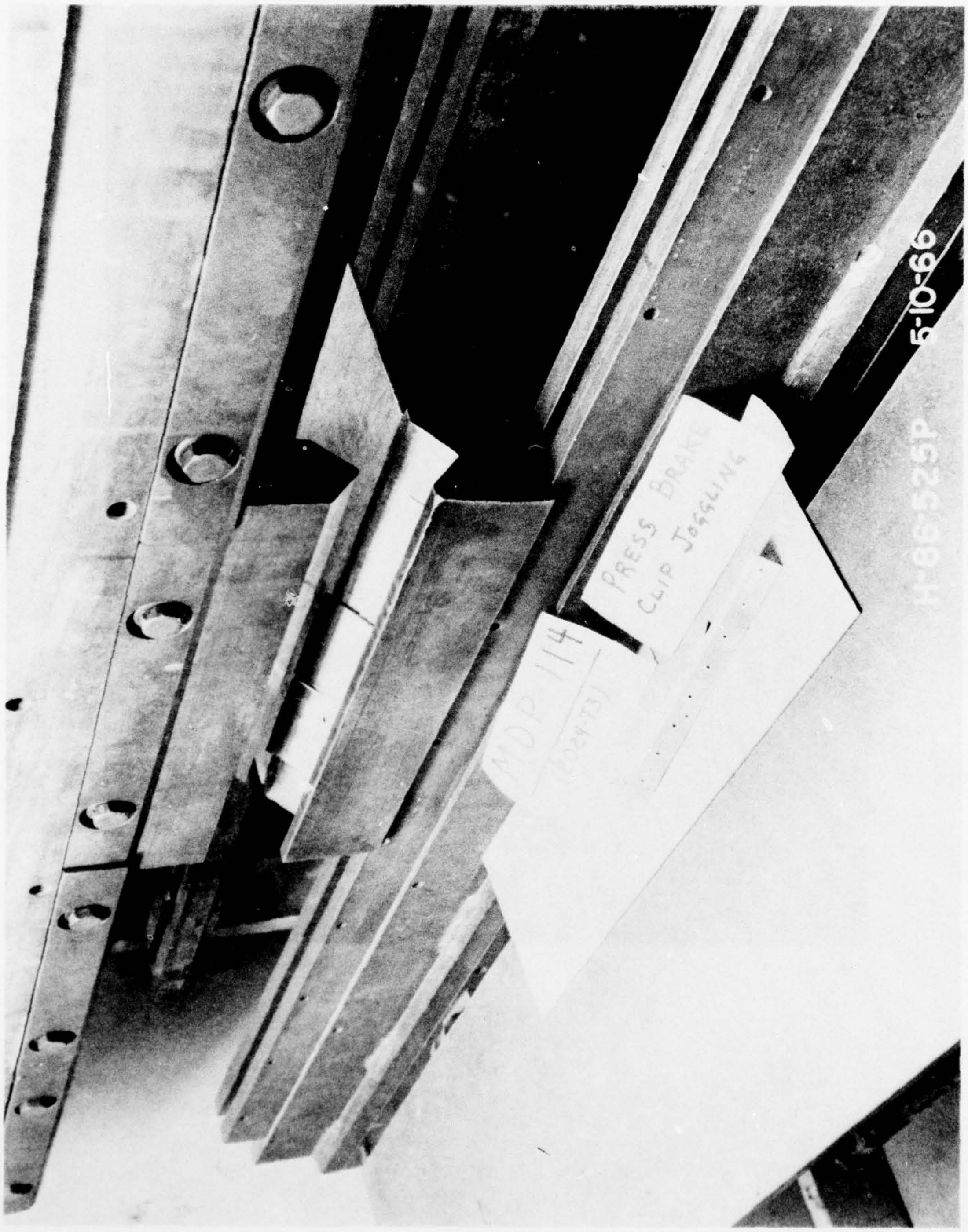


FIGURE 6. PHOTOGRAPH OF 90° V-BLOCK DIES AND SHIMS USED FOR CLIP JOGGLING IN PRESS BRAKE.

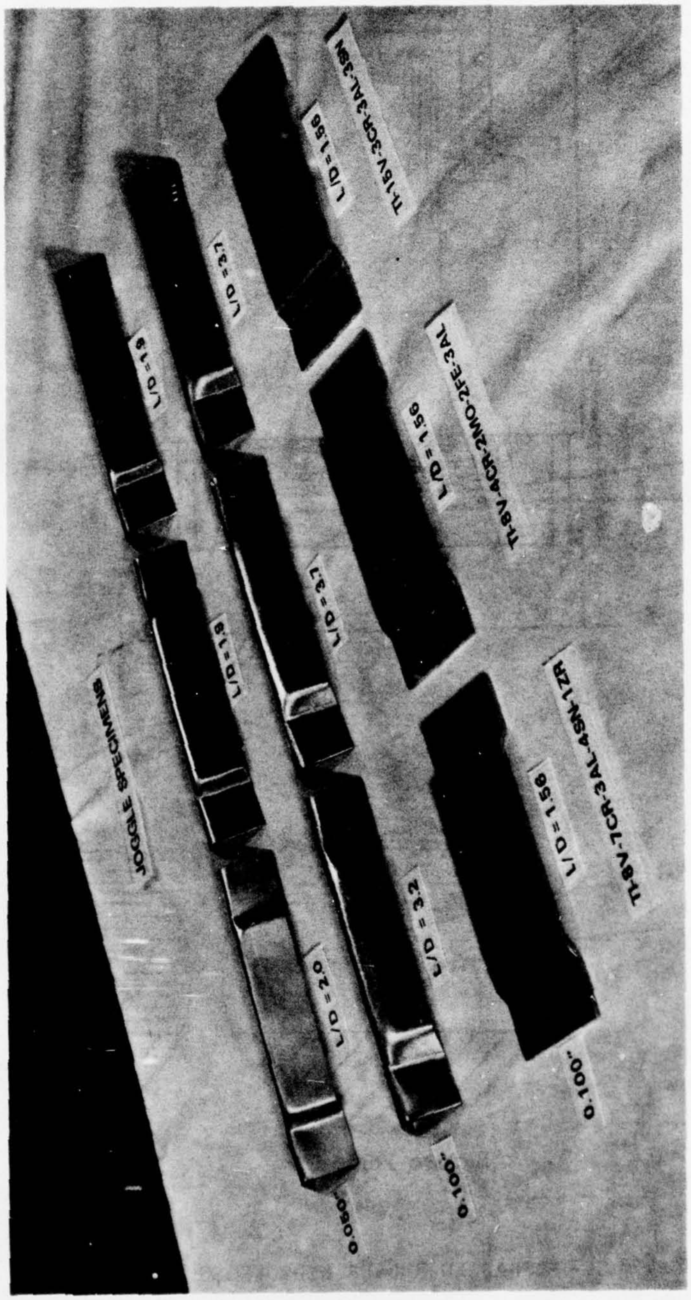


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FIGURE 7. JOGGLE SPECIMENS OF 0.050" AND 0.100" SHEET FROM THREE BETA TITANIUM ALLOYS

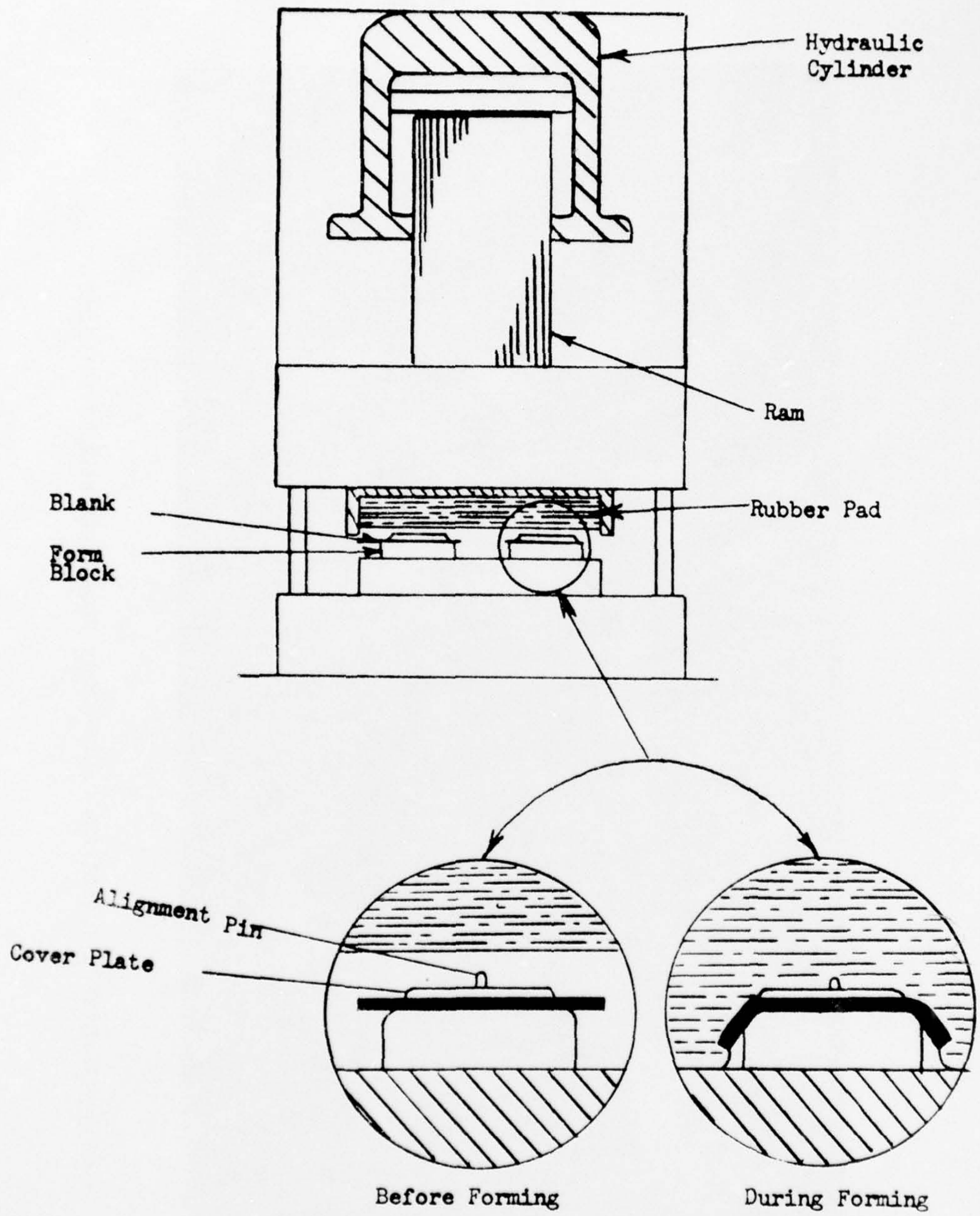

FIGURE 8. SKETCH OF TRAPPED RUBBER HYDROPRESS FORMING.

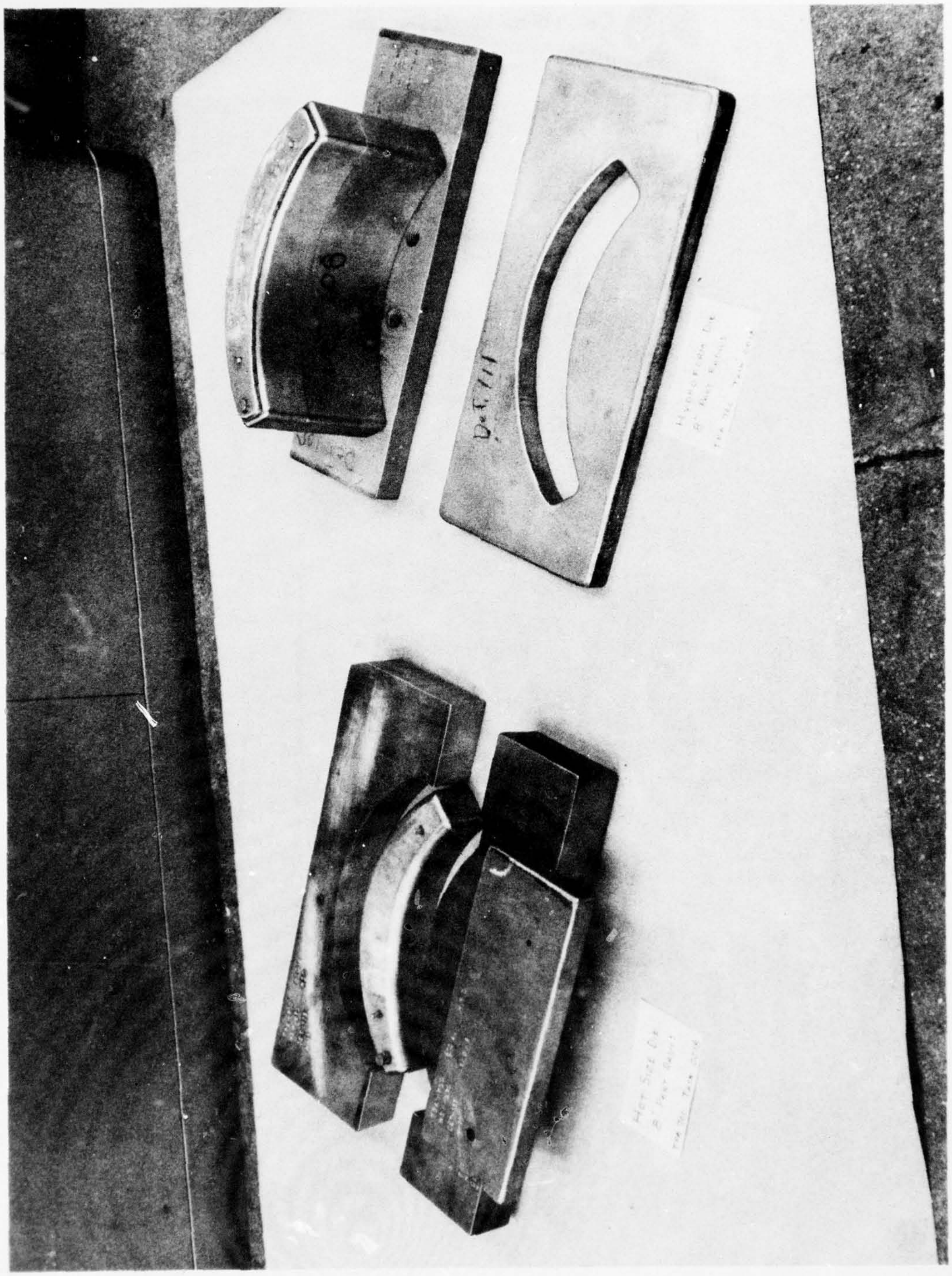

FIGURE 9. PHOTOGRAPH OF HYDROFORM (DRAW FORM) TOOLING FOR STRETCH AND STRETCH FLANGES WITH 8" PART RADIUS (RIGHT SIDE)

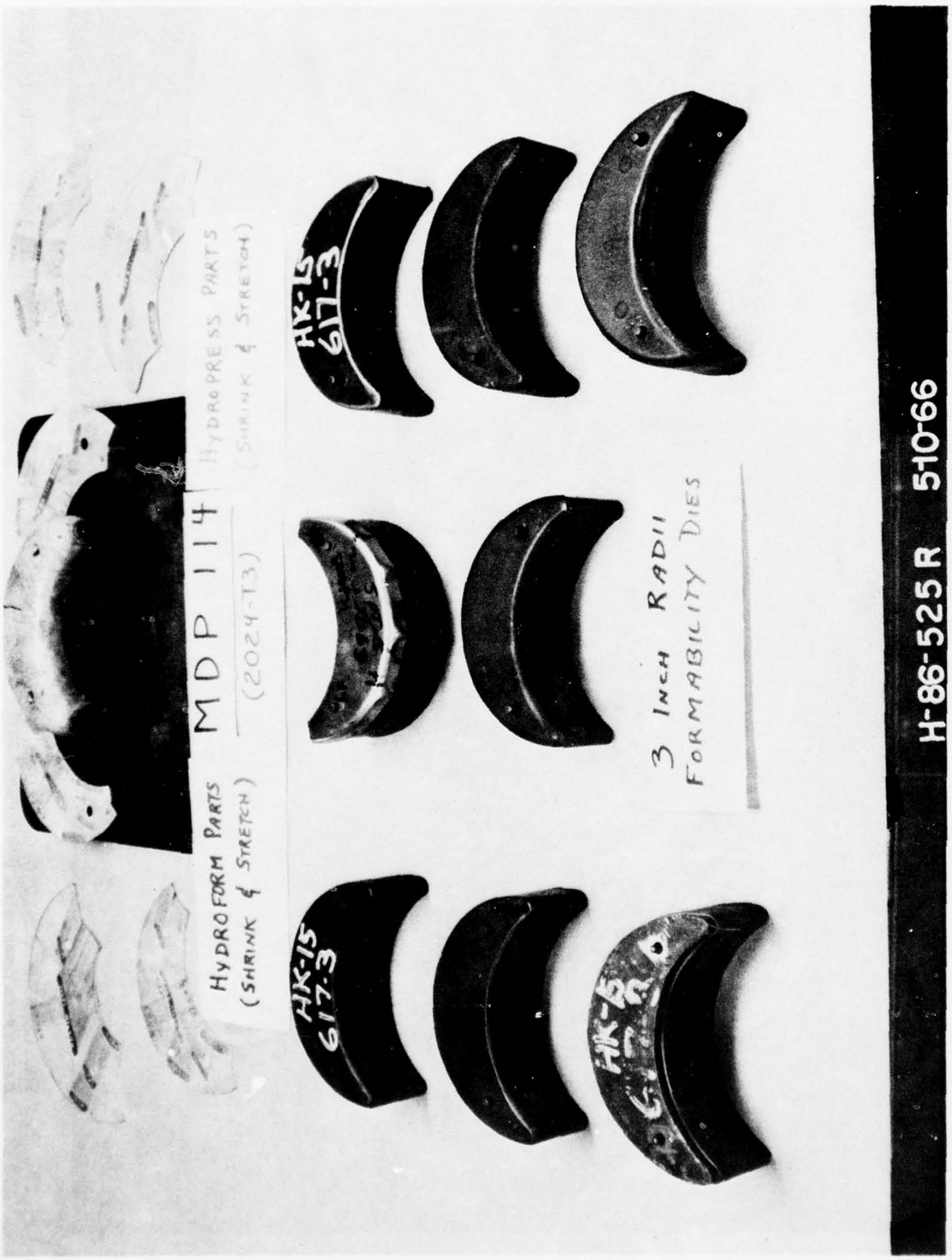

FIGURE 10. PHOTOGRAPH OF HYDROFORM AND HYDROPRESS MALE DIES FOR STRETCH AND SHRINK FLANGES WITH 3" PART RADIUS

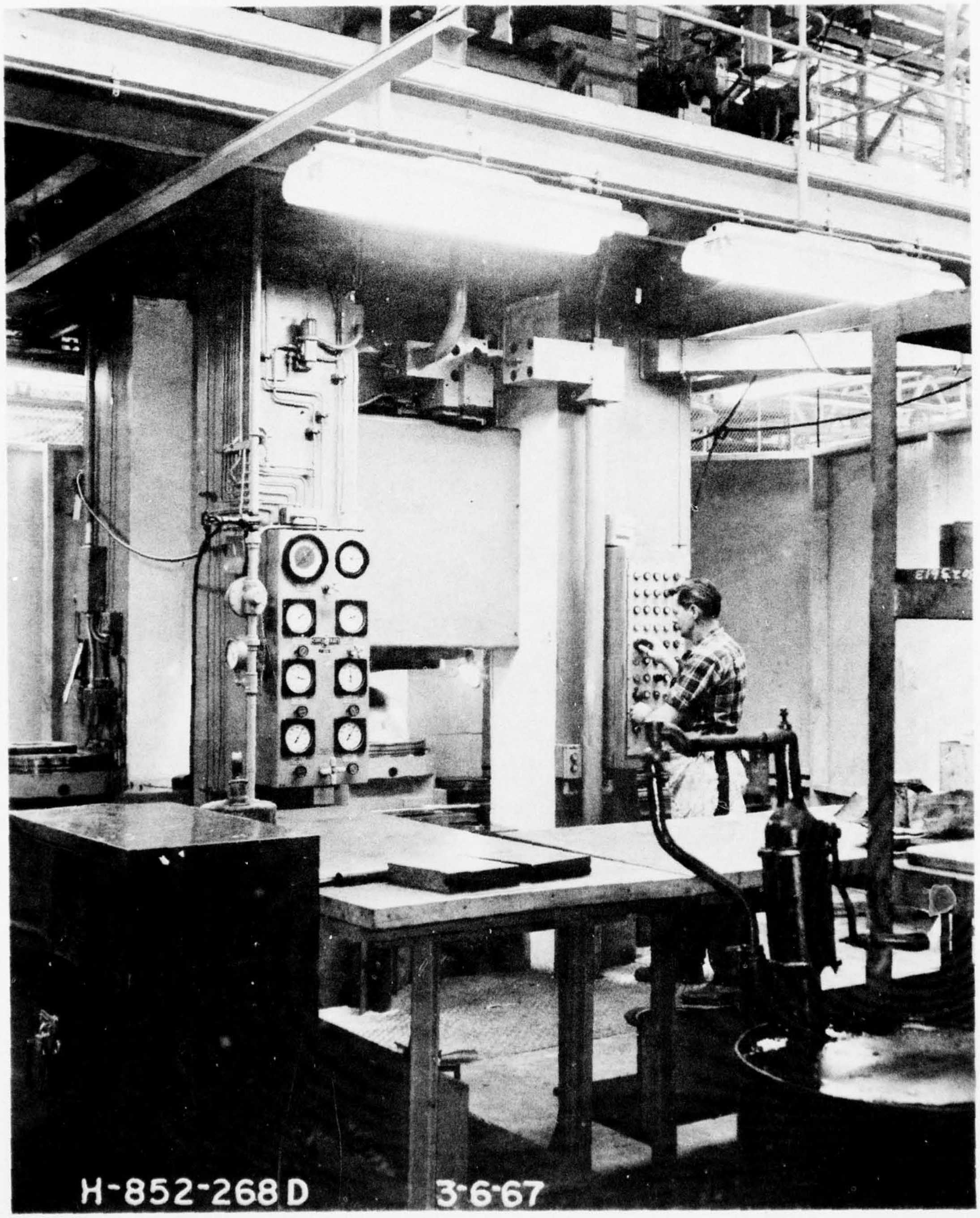

FIGURE 11. PHOTOGRAPH OF 2700-TON CINCINNATI HYDROFORM PRESS WITH 25" DIAMETER RAM (10,000 PSI CAPACITY)

10309

FIGURE 12. HYDROPRESS FORMED SAMPLES (3" PART RADIUS) FROM 0.050" SHEET OF THREE BETA TITANIUM ALLOYS (26 AND 29 PERCENT STRETCH FLANGES AND 11-25 PERCENT SHRINK FLANGES, VIEW OF CONVEX SIDE).

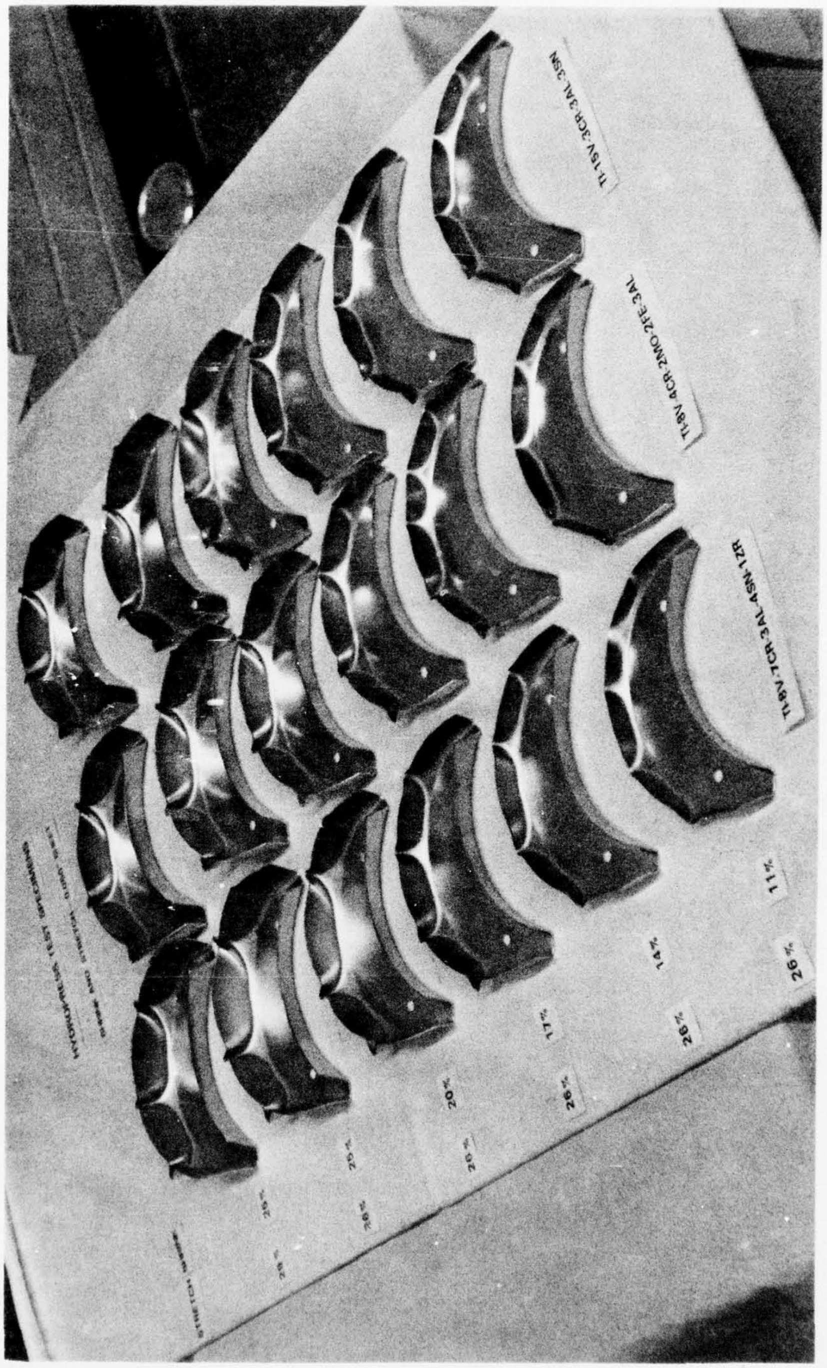

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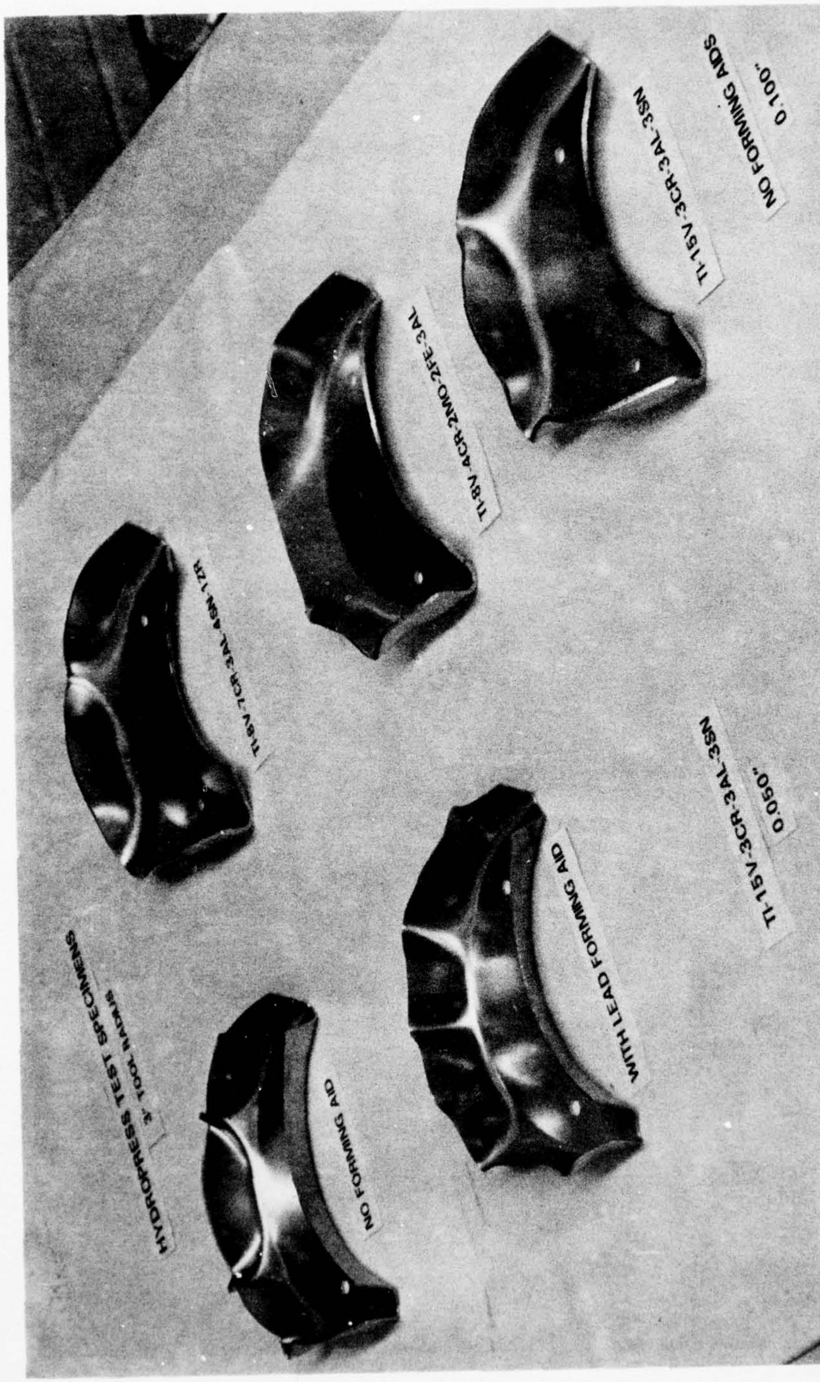
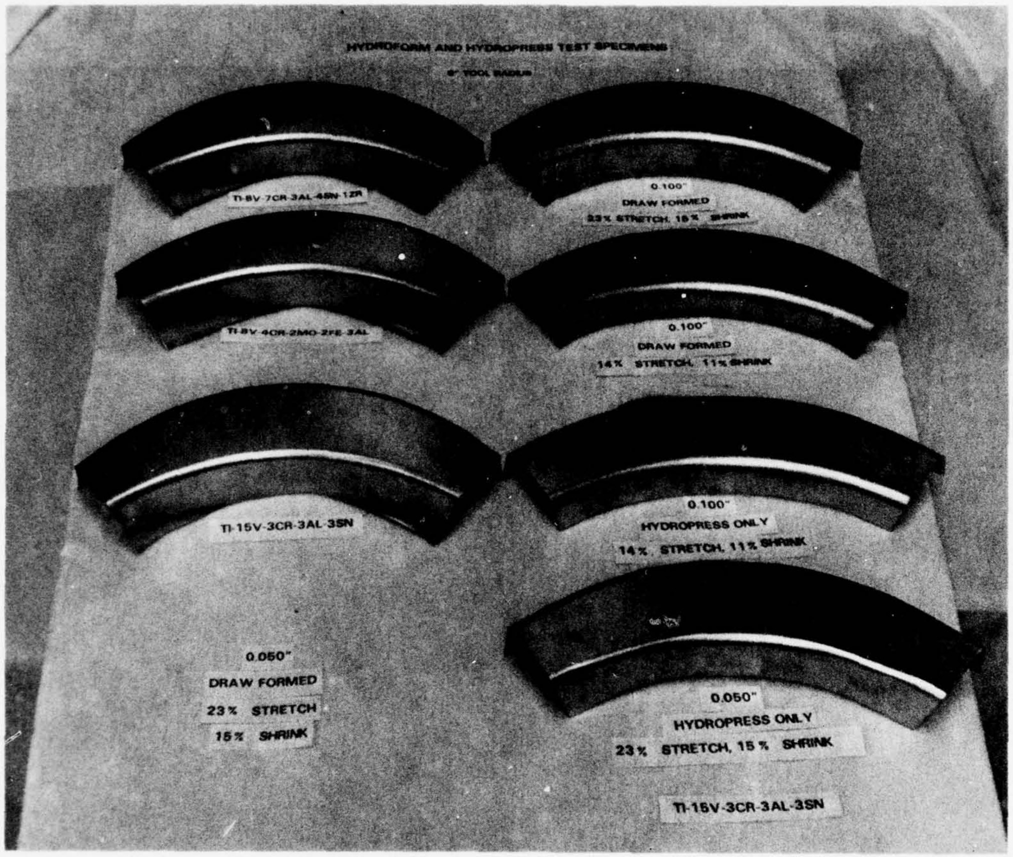
FIGURE 13. HYDROPRESS FORMED SAMPLES (3" PART RADIUS) FROM 0.050" SHEET OF THREE BETA TITANIUM ALLOYS (26 AND 29 PERCENT STRETCH FLANGES AND 11-25 PERCENT SHRINK FLANGES, VIEW OF CONCAVE SIDE).



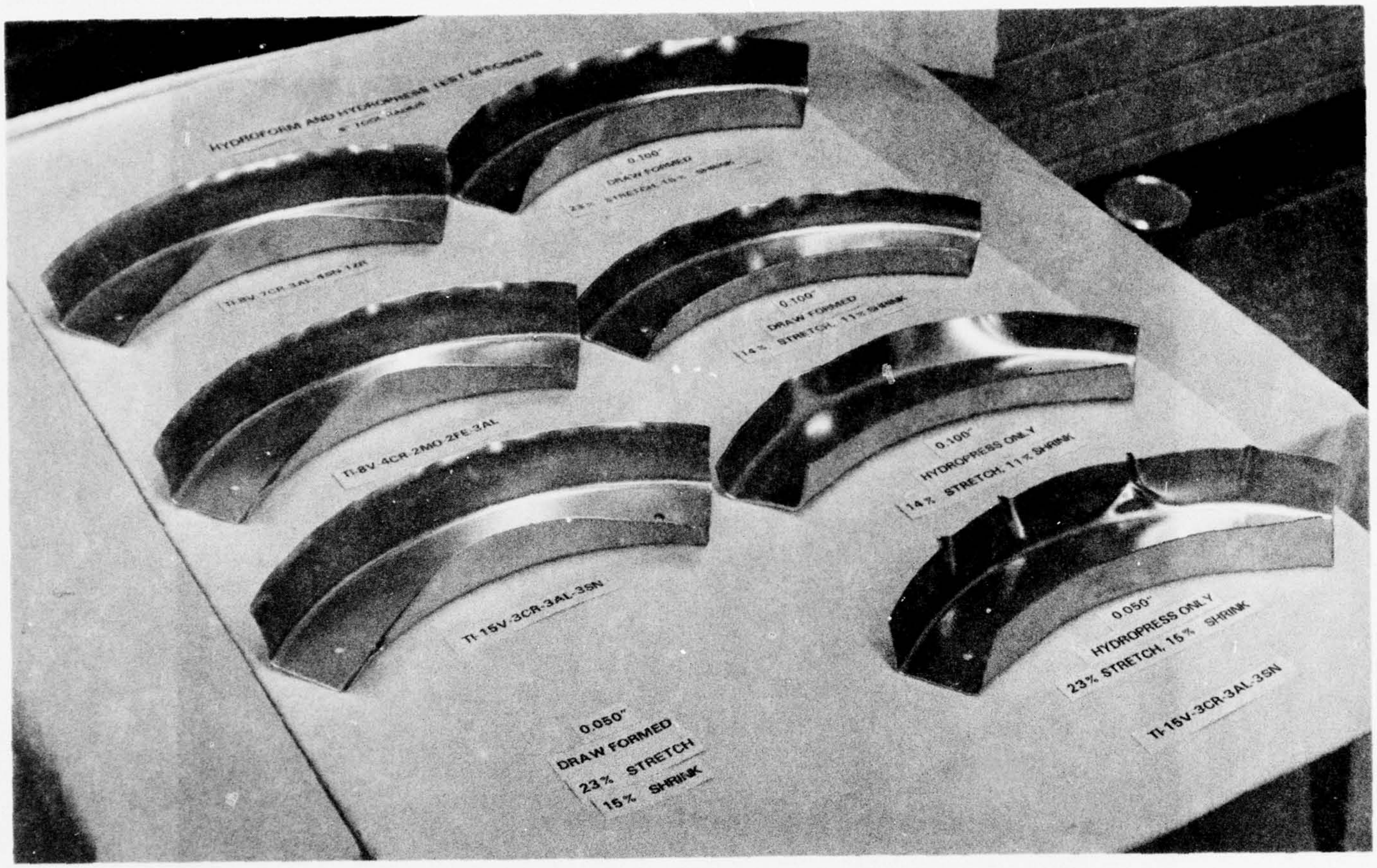
10316

FIGURE 14. HYDROPRESS FORMED SAMPLES (3" PART RADIUS) OF 0.050" AND 0.100" SHEETS FROM THREE BETA TITANIUM ALLOYS SHOWING INCOMPLETE FORMING OF 0.100" MATERIAL AND MORE OPEN BUCKLES OBTAINED WITH LEAD FORMING AID ON 0.050" SHEET (VIEW OF CONCAVE SIDE).



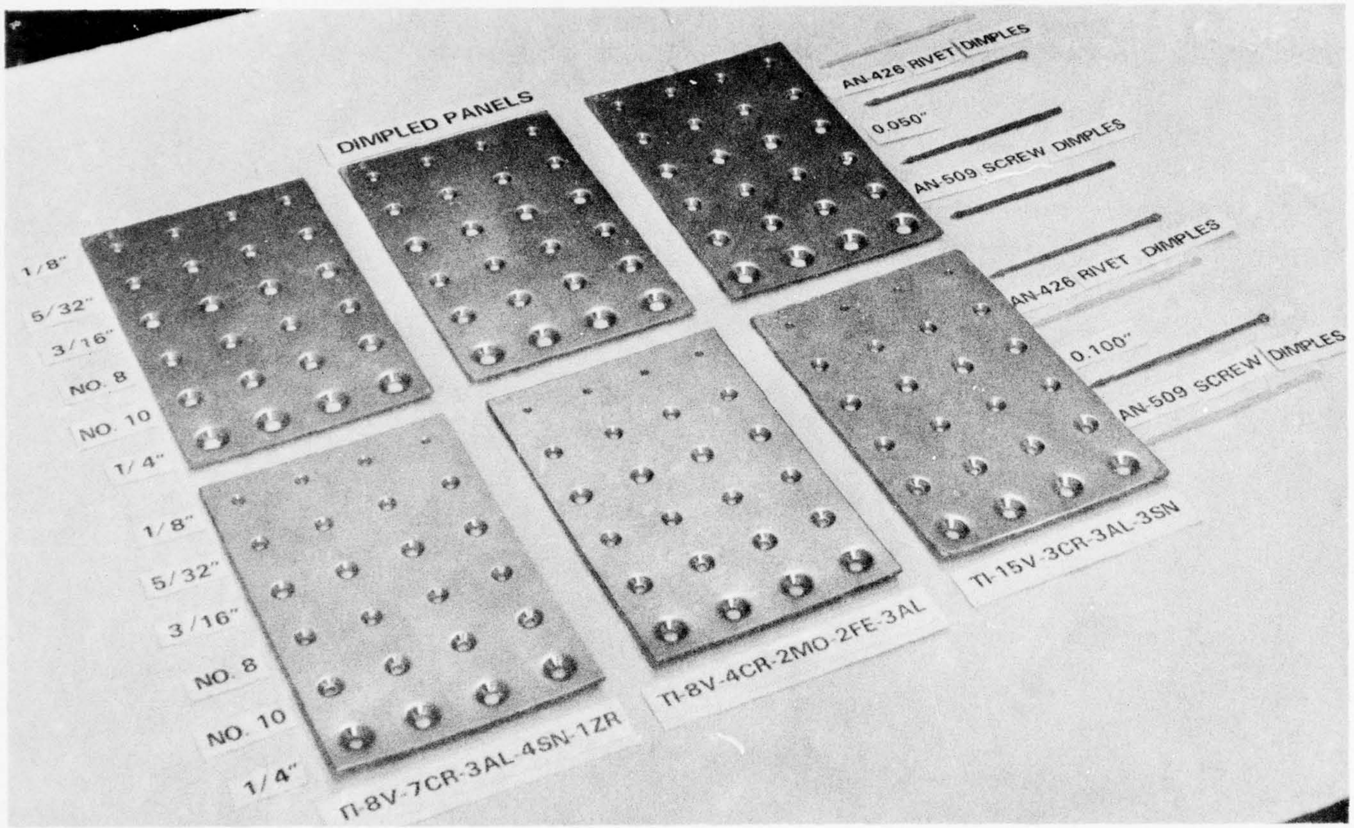
10313

FIGURE 15. HYDROFORM (DRAW FORMED) AND HYDROPRESS TEST SPECIMENS (8" PART RADIUS) FROM 0.050" AND 0.100" SHEETS OF THREE BETA TITANIUM ALLOYS (VIEW OF CONVEX SIDE).



10317

FIGURE 16. HYDROFORM (DRAW FORMED) AND HYDROPRESS TEST SPECIMENS (8" PART RADIUS) FROM 0.050" AND 0.100" SHEETS OF THREE BETA TITANIUM ALLOYS (VIEW OF CONCAVE SIDE SHOWING ADVANTAGES OF DRAW FORMING IN REDUCING SHRINK FLANGE WRINKLES AND LESS SPRINGBACK IN HYDROPRESS-FORMING THE STRETCH FLANGE).



10308

FIGURE 17. PHOTOGRAPH OF SIX 4" x 6" DIMPLED PANELS OF 0.050" AND 0.100" SHEETS FROM THREE BETA TITANIUM ALLOYS (RIVET AND SCREW DIMPLES IN REPLICATES OF FOUR IN EACH HORIZONTAL ROW FOR EACH DIMPLE SIZE).

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5) Private communication from Mr. J. A. Hall.

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